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Long-Term Life Testing of Geostationary Operational Environmental Satellite (GOES) Encoder Lamps

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National Aeronautics and
Space Administration

Office of Management

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FOREWORD

The Geostationary Operational Environmental Satellite (GOES) system is a joint project between the National Aeronautics and Space Administration (NASA) and the Department of Commerce (DOC). The project is managed for NASA by the Goddard Space Flight Center (GSFC) and for DOC by the National Environmental Satellite Service (NESS) of the National Oceanic and Atmospheric Administration (NOAA).

During the summer and fall of 1979, GOES was having technical difficulties. Three spacecraft had been launched between October 1975 and June 1978. The Earth-imaging instrument payload for these satellites is the Visible Infrared Spin-Scan Radiometer (VISSR). The VISSR on two of the three spacecraft had either malfunctioned or was performing poorly, prompting NOAA to request an investigation by NASA. In October 1979, I was asked to head a "Tiger Team" whose charter was to review in-orbit data, the VISSR mirror drive and the optical encoder for failure, design characteristics and deficiencies. Out of this investigation came identification of the encoder lamps as a weak point in the instrument's design.

Spacecraft and engineering anomalies are rarely simple, one-dimensional problems. Typical of the genre, this problem was a complex mixture of design, processing and materials. Early in the investigation, we determined that the lamps were failing prematurely. Due to a lack of reliable data, however, we were unable to pinpoint the cause of failures as being poor processing (back-filling and sealing techniques), material choice (pure tungsten versus doped material) or system operating parameters (lamp voltage and filament size). After 12 years of testing we can say, with confidence, that we understand why the lamps failed prematurely and, as typically is the case, there was not just one cause. This work, which picked up on and implemented the committee's recommendations, is a valuable catalog of archival information and lessons learned for GOES as well as for future spacecraft.

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INTRODUCTION

At the request of the Associate Administrator for Space and Terrestrial Applications, a "Tiger Team" was established at Goddard Space Flight Center (GSFC) in October 1979 to perform an investigation of the scan mirror drive systems in the Visible Infrared Spin-Scan Radiometer (VISSR) and its successor -- the VISSR Atmospheric Sounder (VAS). This request was prompted by the failure of optical shaft encoders in the VISSR of two Geostationary Operational Environmental Satellites (GOES-2 and GOES-3). The final report of the Tiger Team's investigation was published in May 1980.[1] The Tiger Team determined that the encoder failures were due to either lamp burn out or degradation of lamp light output. One of the recommendations of the Tiger Team was as follows: "Conduct a test program using a sufficient quantity of encoder lamps to obtain statistical data on bulb parameters. There is presently no statistical data on useful or ultimate bulb life."

Spurred by the Tiger Team's recommendation, the Materials Branch at GSFC began life tests of appropriate lamps in 1980. This report discusses the results of more than ten years of tungsten filament lamp life testing. This report also functions as an archive for the data gathered over this period. All of the 49 lamps, tested in four separate experiments, were similar to the lamps used in GOES-5 through GOES-7, and GOES-G.† These lamps were operated at various constant DC voltages between 3.5 and 5.0 volts -- the operating range of the flight lamps. The electrical current and lamp light output were measured during the life tests. Twenty-four of the lamps tested had filaments constructed from GE-218W tungsten wire††, which was used in the encoder lamps for GOES-5 and GOES-6. The other lamps had filaments constructed from GE-218W or Luma tungsten wire†††, doped with either rhenium or thoria. GE-218W tungsten wire doped with rhenium was employed in the lamps in GOES-G encoders and is currently being flown on GOES-7.

The life test data have been instrumental in identifying the lamp failure mechanisms, in successfully predicting the in-flight failure of encoders lamps in three GOES spacecraft, and in providing design modifications which have extended encoder life. The technique developed by Viehmann and Helmold for predicting lamp lifetime is described in Reference 2, and will not be discussed in this report. This technique is based on the operating voltage of the lamp.

The short lamp lifetimes determined from this testing influenced modifications in GOES-6 and GOES-7. Each VISSR/VAS instrument has two encoders mounted on the shaft used to control the positioning of the optics in the instrument. These encoders have been designated "primary" and "redundant." The encoders in GOES-1 through GOES-5 had one lamp in each encoder. The encoders in GOES-6 were redesigned to have two lamps each, giving a total of four.

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† GOES-G never reached orbit due to a launch failure.

†† Filament wire was supplied by General Electric, Cleveland, Ohio.

††† Filament wire was also supplied by Luma Metall Corporation, Kalmar, Sweden.

Major redesigns of the encoders in GOES-7 allowed the lamps to be operated at below 3.0 volts. Encoder lamps in the previous satellites were operated between 4.0 and 5.0 volts. A second type of encoder was also designed for GOES-7 which uses light emitting diodes (LEDs) instead of lamps. GOES-7 has both a lamp encoder and an LED encoder, each with redundant light sources. The use of LEDs and lamps operating at lower voltages, virtually ensures that the encoders will not be the life-limiting mechanism in this satellite. GOES-7 (the last in this satellite series) was launched in February 1987, and was still operating on its first LED without problems at the time of this report. The lamp encoder is being used for backup on GOES-7.

OBJECTIVES

The objectives of the GOES Encoder Lamp Life Test Program conducted by the Materials Branch were to obtain long life expectancy encoder lamps by strict manufacturing process control, filament material selection, and de-rated voltage operation.[2] The Materials Branch pursued the following specific objectives to accomplish these goals:

- Determining lamp aging characteristics as a function of voltage,
- Determining the ultimate lamp lifetime as a function of voltage,
- Comparing laboratory results to in-orbit experience,
- Predicting operational lifetimes for GOES-5 and GOES-6 encoders,
- Finding operational conditions which will maximize the useful life of a lamp.

Later additions to these objectives were determining the best filament material for GOES-G and GOES-7, and predicting the operational lifetimes for GOES-7 encoders.

HISTORY OF ENCODER LAMP PROBLEM

The NASA meteorological satellite program dates back to the early 1970's. This program began with the development and successful launching of two satellites under the Synchronous Meteorological Satellite (SMS) project in 1974 and 1975. These two satellites (SMS-1 and SMS-2), along with GOES-1, GOES-2, and GOES-3 were built by the Ford Aerospace Corporation, Newport Beach, California. GOES-4 through GOES-7, and GOES-G were built by the Hughes Aircraft Company, Los Angeles, California.

The primary mission of these satellites is to provide weather data. This data is gathered by the VISSR, which is built by a subsidiary of Hughes -- the Santa Barbara Research Center (SBRC), Goleta, California. The scan drive system in the VISSR is controlled by an optical encoder which is manufactured by Baldwin Electronics Inc., Little Rock, Arkansas. The lamps used in these encoders are supplied by the Herzog Miniature Lamp Works Company, Long Island City, New York.

SMS-1 was launched in May 1974. This satellite was no longer useable after January 1981, when all of its fuel was depleted. The redundant encoder lamp on this satellite completed 24 months of operation (and was still useable) up to January 1981. The primary encoder lamp was never used. The second of these prototype satellites, SMS-2, was launched in February 1975. The redundant encoder lamp on SMS-2 burned-out (failed open) after 4 years and 11 months of operation. The primary encoder lamp completed 8 months of operation (and was still useable) before the scan drive circuitry in the VISSR failed. This satellite was no longer useful after August 1981.

The first satellite of the GOES series was launched in October 1975. Figure 1 shows the encoder lamp operational history for SMS and GOES spacecraft. This figure also shows the timing of laboratory testing performed by the Materials Branch. The redundant encoder lamp in GOES-1 had a total of 18 months of operation before burn out, and the primary lamp had a total of 31 months of operation before burn out. This satellite was no longer useable after February 1985. Up to this satellite, encoder lamp performance did not appear to be a problem.

As mentioned earlier, it was the short useful life of the lamps in GOES-2 and GOES-3 that triggered the investigation by the GSFC Tiger Team. GOES-2 was launched in June 1977, and GOES-3 followed in June 1978. The redundant encoder lamp in GOES-2 lasted 18 months before burn out, and the primary encoder lamp lasted a month before degraded light output of this lamp caused the encoder to stop operating correctly. The redundant encoder lamp on GOES-3 lasted 15 months before low light output caused the encoder to stop working, and the primary encoder lamp lasted 18 months before low light output shut down the instrument.

GOES-4 was launched in September 1980, and after 26 months of operation a single point PC board failure disabled the VISSR/VAS system in this satellite. The redundant encoder lamp was still operating at the time of this failure, and the primary encoder lamp was never operated.[3]

All the lamps used in SMS and GOES spacecraft were manufactured by the Herzog Miniature Lamp Works Company. The manufacturing process included winding the filaments, evacuating the glass envelope, and backfilling the base of the lamp. Herzog considered this process proprietary. The lamps in SMS-1, SMS-2, and GOES-1 were manufactured in 1970. The lamps for GOES-2 were manufactured in 1976, and the lamps for GOES-3 and GOES-4 in 1974. An investigation by SBRC indicated that changes had occurred in this process between 1970 and 1974, which probably caused the premature failure of GOES-2 and GOES-3 encoder lamps.[4]

Subsequent to this, the lamps for GOES-5 through GOES-7 were assembled by Herzog (including the winding of the filaments), but the evacuation of the glass envelope and the backfilling of the base of the lamp were now done by SBRC. SBRC took over this part of the lamp fabrication to establish better process control of the lamp assembly.[1] The lamps tested by the Materials Branch were fabricated using the two-stage process developed for the encoder lamps used in GOES-5 through GOES-7.

GOES-5 was launched in May 1981. Its redundant encoder lamp burned-out after 25 months of operation, and the primary encoder lamp burned-out after 14 months. It's failure after 39 months of operation (due to encoder lamp burn out) started a second investigation of the lamp problem by the Hughes Aircraft Company.

GOES-6 was launched in April 1983. Its encoders were modified to use two lamps each, extending the useful life of the encoder system by using four lamps instead of two. The ultimate failure of the VISSR/VAS system in this satellite was due to encoder lamp burn out. The four lamps in this satellite had a combined lifetime of 70 months (5 years, 10 months). The lamps lasted 27, 13, 14, and 16 months respectively. The VISSR/VAS instrument was designed to have a mission life of seven years.

EXPERIMENTS

Description of Lamp

The encoder lamp is shown in Figure 2. It has a straight singly coiled filament 3.875 mm in length wound from 38 μm diameter tungsten wire on a 135 μm diameter mandrel with a pitch of 16 turns/mm for a total of 62 turns. The filament is either welded or brazed to the support posts. The cylindrical glass envelope has a diameter of about 12 mm and is 17 mm long. The lamp is soldered into a brass base for precision mounting and positioning. The fill gas is krypton at 14.0 psi.[2]

The lamps tested at GSFC had lengths varying between 3.1 and 4.7 mm, and the total number of turns varied between 50 and 74. The diameter of the tungsten wire also varied between 36.3 and 39.5 μm.

Experiment 1

The purpose of Experiment 1 was to determine the effects of the improved backfilling technique developed by SBRC for the GOES-5 and GOES-6 encoder lamps, and to determine lamp lifetime when operated at 5.0 volts.[5] The investigation by the GSFC Tiger Team revealed that the two most likely causes of failure of the GOES-2 and GOES-3 encoder lamps were water cycling in the lamps, and differential thermal expansion between the hard epoxy backfill and the glass envelope.

The water cycle in a lamp removes tungsten from the filament and deposits it on the glass envelope, as evidenced by darkening of the glass envelope. Water molecules dissociate at the hot filament into hydrogen and oxygen. The oxygen forms tungsten oxide, which is then transported to the glass envelope. The oxide is reduced by free hydrogen, and the cycle is repeated. Differential thermal expansion between the envelope and epoxy causes the epoxy to crack, allowing ambient gases into the envelope. As a result, SBRC developed a better envelope evacuation technique to remove any water in the lamps, and used backfill materials that were more compatible with the glass envelope.[1]

Experiment 1 started on August 1, 1980. This experiment consisted of six lamps having filaments constructed from GE-218W tungsten wire. These filaments were welded to the support posts. All six lamps were "burned-in" for 21 days (part of the flight screening procedure). Lamps 1 and 2 were similar to the encoder lamp specification, but had longer filaments with more turns. An encoder lamp typically has 62 turns, while Lamps 1 and 2 had 74. These two lamps were operated at 6.0 volts to compensate for their greater length and number of turns. Lamps 3 and 4 were identical to the encoder lamps, but were rejected for flight usage due to excessive burn in slope. For a lamp to pass the burn in test, the lamp current can not change by more than 1% for the last two weeks of the burn in period. (Lamp 4 actually passed the burn in test with a 0.92% decrease in current.) Lamps 5 and 6 were flight quality lamps, except they had incorrect mounting hole orientation.

The six lamps in Experiment 1 were mounted on a turntable with light detectors mounted in fixed positions above and along side the turntable as seen in Figure 3. When light output measurements were made on the lamps, the turntable was rotated so that the lamp being tested was positioned under the detectors. When measurements on that lamp were completed, the turntable was rotated to the next lamp. Kepco CK8-5 power supplies were used to supply a constant DC voltage to the lamps. Keithley 160A digital multimeters were used to measure the current through the lamps and the current from the light output detectors. The current through each lamp, and the light output from the front face and the side of each lamp were measured once every three days during the tests. The broadband light output seen by the detectors from each lamp was measured, and the light output at selected spectral frequencies was also measured. The wavelengths that the light output was measured were 570, 700, and 800 nanometers. The light measurements were made using an EG&G 585 radiometer with a 585-63 detector head, and a UDT 21A power meter with a Pin10DP photodiode.

Experiment #2

The purpose of this experiment was to determine lamp light output degradation and lamp lifetime as a function of operating voltage.[5] The lamps were tested at 4.48, 4.67, 4.86 and 5.00 volts -- the voltage values being obtained with the new steppable lamp power supply developed for GOES-5. The development of this power supply was another recommendation of the GSFC Tiger Team.

Experiment 2 began on February 17, 1982. The test specimens for this experiment were 12 flight qualified lamps from the GOES-5 lot with filaments constructed from GE-218W tungsten wire. The filaments were welded to the support posts, as in Experiment 1. All twelve lamps were burned-in at 5.0 volts for varying lengths of time. Lamps 1-4 were operated at 4.48 volts; Lamps 5-7 at 4.67 volts; Lamps 8-10 at 4.86 volts; and Lamps 11 and 12 at 5.00 volts.

The twelve lamps in Experiment 2 were mounted in fixed positions. Each lamp had a dedicated power supply and two dedicated silicon solar cells to measure the light output from the front face and from the side of the lamp. Figure 4 is a photograph of Experiment 2. The voltage across each lamp, the current through each lamp, and the light output measured by the two solar cells mounted with each lamp were manually recorded three times a week (Monday, Wednesday, and Friday). A Fluke 8502A multimeter measured the voltage across and the current through each lamp. A Keithley 173A multimeter measured the current through each solar cell (light output). The solar cells were manufactured by Solarex (part number 4S873). The power supplies used were manufactured by Lambda (model number LCS-2-01). The switch panel used to connect the lamps to the multimeters was designed and constructed by the Materials Branch.

Experiment #3

This experiment was originally started to investigate low voltage burn in characteristics.[5] The operating voltages selected for these life tests were 3.54 and 4.48 volts. At the time of this experiment, the expected operating range for the encoders was between 3.54 and 4.48 volts.

Experiment 3 started on June 11, 1982. This experiment involved test of four lamps with filaments constructed of GE-218W tungsten wire. These filaments were welded to the support posts. Since none of the lamps had a burn in period, it was not determined if they were of flight quality. Lamps 1 and 2 were operated at 3.54 volts; and Lamps 7 and 8 were operated at 4.48 volts. The non-sequential numbering resulted from original plans for testing additional lamps. The instrumentation for this experiment was the same as that used for Experiment 2. The four lamps of Experiment 3 were housed in unused test stations from Experiment 2.

Experiment #4

The intent of this experiment was to determine the effects different filament material had on lamp characteristics as a function of time.[5] It was believed that lamps used in SMS-1 and SMS-2, and GOES-1 were constructed from tungsten wire doped with thoria (thorium dioxide), in an effort to slow down the grain growth which occurs in these lamps.[2] Doping with rhenium has also been shown to retard grain growth.[6] Since by this time we had determined that it is this grain growth which typically causes burn out, the impact of dopants on lamp performance was an important factor to study.

Experiment 4 was started on October 24, 1983. This experiment involved test of twenty-seven lamps with filaments constructed of tungsten or tungsten doped with either rhenium or thoria. All filaments were brazed to the support posts, except the filaments of Lamps 40 and 41, which were welded to the posts. The non-sequential numbering of the lamps is once again due to original plans for additional test stations. The filament material for Lamps 1-9 was tungsten doped with 3% rhenium (GE 3D-EESM). The filament material for Lamps 10-18 was tungsten doped with 1% thoria (GE NF-EPSM). The filament material for Lamps 19-26 was pure tungsten (Luma 821-42). The filament material for Lamps 28-36 was tungsten doped with 3% rhenium (Luma 861-42). The filament material for Lamps 40 and 41 was pure tungsten (GE-218W).

As in Experiment 3, there was no burn in period for these lamps. Thus it was not determined if the lamps were of flight quality prior to testing. Examination of the first three weeks of operation of the eleven lamps operated at 5.00 volts showed that four would have passed the burn in test (lamps 7, 9, 16, and 17), two were borderline (lamp 18 - 1.07%

decrease, and lamp 26 - 1.02% decrease), and five were clearly not flight quality (8, 25, 34, 35, and 36).

The instrumentation used in this experiment was similar to that in Experiments 2 and 3, except that all the data were gathered and stored by a computer (both a Fluke 1720A and later a Fluke 1722A Instrument Controller were used). This allowed data to be measured and recorded daily. The switch panel used in Experiments 2 and 3 to connect the various lamps and solar cells to the multimeters was replaced by a Fluke 2205A Switch Controller (multiplexer), which was controlled through an IEEE-488 interface. Lambda LDS-Y-01 power supplies were used in this experiment. Only one multimeter (a Fluke 8502A) was used in this experiment, which was also controlled through an IEEE-488 interface. The data recorded by the instrument controller were periodically transferred to a DEC PDP-11/23 computer for long-term storage and analysis.† Figure 5 shows a schematic diagram of one test station from Experiment 4. The switching scheme to measure lamp current, described in Figure 5, was used in all four experiments.

The availability of automated data acquisition allowed for the development of a filament scanning device. Using the instrument controller and multimeter from this experiment, a device was developed to measure the light output from a lamp as a function of position along the filament. A schematic diagram of this device can be seen in Figure 6. A lens was used to project an image of the filament onto a solar cell. A small slit (perpendicular to the filament axis) allows only a small "slice" of the projected image through to illuminate the solar cell. The solar cell assembly is mounted on a precision threaded shaft rotated at low speed by a constant speed motor. The current through the solar cell (light output) is measured at set intervals while the solar cell scans across the filament image.

DATA

The data for all 49 lamps tested by the Materials Branch is contained in the attached Appendix. The Appendix contains a summary page for each lamp which lists the lamp's physical dimensions, operating conditions during the life test, and serial or part number assigned to that lamp by SBRC (if available). The summary sheet also has a graph of the pre-life test characteristics of each lamp (the light output and filament current as a function of voltage). This summary sheet has two graphs showing the filament current and light output vs. time during the life test. Some of the lamps (all of Experiment 4, and a few others) have spatial filaments scans showing the light output vs. position along the filament measured at various times during the life test. Up to four of these scans are on the second page for each lamp record.

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† An IBM PC compatible replaced the PDP-11/23 in 1986, and was in turn replaced by a Macintosh II in 1991.

ANALYSIS & DISCUSSION

Ground Testing vs. Application

The data from all four experiments show that SBRC's backfilling technique virtually eliminated lamp envelope darkening (the suspected cause of the low light output failures in GOES-2 and GOES-3). Only three of 49 lamps tested showed any signs of envelope darkening (all from Experiment 1). Our tests indicated however that an encoder life would still be limited by premature failure of the lamp. Figure 7 is a plot of lamp lifetime to burn out for the lamps tested by the Materials Branch. This data shows that even with the improved process for constructing lamps, only the lamps operated at 3.54 volts can be deemed capable of lasting seven years -- the expected mission life of the VISSR/VAS system.

The GE-218W lamps tested by the Materials Branch displayed similar lifetime characteristics as the encoder lamps used in GOES-5 and GOES-6. As shown in Figure 8, the GOES encoder lamps and those tested at GSFC have no significant difference in lifetime characteristics.

Lifetime Predictions

The data from the GE-218W lamps were used to predict the in-orbit failure of the two lamps on GOES-5, and of all four lamps on GOES-6. The in-orbit failure of one of the lamps in GOES-1 was also predicted when this satellite was re-activated. A summary of these predictions can be seen in Table 1. The data on GE lamps doped with rhenium from Experiment 4 were used to predict the expected useful lifetime of the two encoder lamps presently being flown in GOES-7.

Table 1. Lamp lifetime predictions for GOES-5, GOES-6, and one lamp on GOES-1 when this satellite was re-activated.

Satellite	Encoder	Actual Lifetime	Pre-launch Prediction	"At Turn-on" Prediction
GOES-5	Redundant	25 months	24 ± 6 months	-----
	Primary	13 months	21 ± 3 months	17 ± 3 months[1]
GOES-6	1st Redundant	14 months	22 ± 3 months	11 ± 2 months[1]
	2nd Redundant	27 months	19 ± 3 months	21 ± 5 months[2]
	1st Primary	16 months	19 ± 3 months	16 ± 6 months[1]
	2nd Primary	13 months	22 ± 3 months	16 ± 4 months[1]
GOES-1	Primary	31 months	----	32 ± 8 months[3]

(1) Initial operating voltage had to be increased.
(2) Initial operating voltage was lowered.
(3) Prediction made when satellite was re-activated.

Lamp lifetime predictions for GOES-5 and GOES-6 were made by Walter Viehmann in August 1983, using the lifetime projection techniques developed in Reference 2. GOES-5 had been launched and was still operating with its first lamp (redundant) when the predictions were made. Later, lifetime projections were modified when each lamp was turned on, to reflect changes in operation conditions. Most of the lamps had to be operated at a higher voltage than their pre-launch setting. It was suspected that the optics in the encoders were distorted during launch, requiring the lamps to be operated at a higher voltage. The prediction for the remaining lamp in GOES-1 was made when this satellite was re-activated in October 1984.

Table 1 does not contain predictions for GOES-7. The lamps in GOES-7 can be operated at below 3.00 volts, which will give them a projected life time of at least 4 years with a 95% confidence, and 9 years with a 50% confidence. This prediction was made by Dr. Henning Leidecker, using the same technique employed by Walter Viehmann.

Lamp Failure Mechanisms

At least three different failure mechanisms have been identified for tungsten and doped-tungsten lamps. For lamps operated at temperatures near the melting point of tungsten, evaporation of the filament is the primary failure mechanism. Preliminary lifetime estimates for the GOES encoder lamps assumed that evaporation of the filament was the primary cause of lamp failure.

The life test program at GSFC showed that grain growth occurring in the filament was the primary cause of lamp failure. At lower temperatures, grain growth in the filament driven by electromigration and the Soret effect is the cause of lamp failure. Electromigration is defined as the preferential migration of ions in a solid when a direct current is passed through the solid. The Soret effect is the transport of mass in a gas, liquid, or solid phase due to a temperature gradient. Both of these mechanisms cause the tungsten ions in the filament to diffuse, eventually forming into large crystals through the center portion of the filament. The turns near the support posts do not change much in structure because the support posts act as heat sinks.[7]

Depending on the composition of the filament, grain growth can cause the filament to fail open by two different mechanisms. For pure tungsten lamps and for lamps made from tungsten doped with a small percentage (1 to 2%) of thoria, the primary failure mechanism is the development of notches in the filament. When these lamps are powered, the temperature gradient across the filament and the electrical current through the lamp cause the tungsten ions to migrate. Small crystal grains present in the filament begin to "grow" into larger crystals. Eventually the center portion of the filament will develop into many large crystals. Since the surface diffusion rate for tungsten ions is different along different crystal planes, periodically spaced notches begin to develop in these crystals. These notches form because the surface diffusion rate along the crystal plane in which these notches occur is highest.[8]

As a notch becomes deeper, the filament will develop a local "hot spot" which indicates an increase in temperature at that point. With an increase in temperature the diffusion rate increases and evaporation may occur, which eventually causes the notch to "etch" completely through the filament. Figure 9 shows an example of these notches. At the time the notch completely etches through the filament, the filament will either have a catastrophic failure or the notch will disappear as the filament rewelds at that point (rewelding is more likely than failure). If rewelding occurs, the filament will continue to operate normally until another notch causes it to fail.

The development of a notch into a hot spot was observed in real time with the automated data acquisition system used for Experiment 4. A plot of the filament current vs. time shown in Figure 10a, reveals a rapid decrease in current several days before a reweld occurs (on day 2033 for this lamp). After the hot spot rewelds, the current returns to a value close to what it was before the onset of the hot spot.

This hot spot was also observed using scans of light output versus position along a filament. The temperature at the hot spot is higher than the rest of the filament, which causes an increase in light output at that point. A filament scan two days prior to reweld (Figure 10b) shows the increased light output at the hot spot. Figure 10c shows the light output vs. filament position the day the reweld occurred. The light output at the hot spot is higher than two days prior. Figure 10d shows the light output vs. filament position two days after the reweld. The hot spot no longer exists, and the light output has a more uniform distribution.

The second failure mechanism associated with grain growth occurs in lamps constructed from tungsten wire doped with a small percentage of rhenium (1 to 5%). The rhenium in the filament retards grain growth, but also causes distortion of the filament (Figure 11). This distortion of the filament will eventually cause adjacent turns to touch, which can cause the development of a hot spot and ultimate failure of the lamp.

Examination of the current through a lamp vs. time can be used to determine the extent of grain growth that has occurred in the filament. For the pure tungsten and thoria-doped lamps, the lifetime of a typical lamp can be divided into three phases as shown in Figure 12. The first phase is characterized by a rapid decrease in current, but lasts only about a month. This phase has been called the "burn-in" phase.

The second phase, called the "grain-growth" phase, is characterized by a slower decrease in current, and a relatively longer duration. During this phase the center portion of the filament is becoming many large crystals. The current decay during this phase is relatively smooth and constant. The third phase, called the "reweld" phase, is characterized by short term rapid decreases in current followed by recovery (as shown in Figure 10a). It is during this phase that notches develop into hot spots. The length of this phase varies greatly, since there is a small probability any hot spot will cause a filament to fail instead of rewelding.

In the rhenium-doped lamps, the current through the lamp vs. time can also be described as having three phases (Figure 13). The first two phases are the same as those in the tungsten and thoria-doped lamps. The size of the crystals developed during the second phase are smaller than for pure tungsten or thoria-doped lamps. The third phase for these lamps, called the "distortion" phase, is characterized by rapid current increases followed by periods of smooth current decay . These increases in current are caused by distortions in the filament which cause part of the filament to be shorted, thus decreasing the electrical path length and the resistance of the filament.

Observed Effects of Doping the Tungsten

Some of the lamps tested in Experiment 4 were constructed from tungsten wire that was doped with 3% rhenium or with 1% thoria. GE-218W doped with 3% rhenium was used in the backup lamps on GOES-7. Both of these dopants were expected to retard grain growth in these filaments, and thus increase the life of these lamps. It has been speculated that the lamps used in SMS-1, SMS-2, and GOES-1 had filaments constructed from tungsten doped with thoria, which was thought to give these lamps a longer lifetime.[2] Data comparing pure tungsten filaments with rhenium-doped and thoria-doped filaments tested at 3.54 and 5.00 volts are shown in Tables 2 and 3 respectively.

Initial examination of the data presented in Table 2 reveals no statistical difference in lamp lifetime for the pure tungsten and rhenium-doped lamps at 3.54 volts. Further interpretation of the data produces three reasons to suggest that the rhenium-doped lamps may have a longer "useful" lifetime (for the encoder application) at 3.54 volts or lower. First, this data shows that the pure tungsten lamps presently have a longer average lifetime, but this may change as there are two rhenium-doped lamps still operating and only one each of the thoria-doped and pure tungsten.

Table 2. Statistics for the 3.54 volts lamps test by the Materials Branch. This table includes data from lamps that are still operating - two rhenium-doped lamps, one thoria-doped lamp, and one pure tungsten lamp. This table excludes data from lamps which burned-out early because of a low number of turns or some other defect.

	Tungsten	Tungsten w. 3% Re	Tungsten w. 1% Thoria
Time to burn out (days)	2754 ± 377	2542 ± 263	2264 ± 342
Time to 1st reweld (days)	1763 ± 806	1450 ± 358	1869 ± 296
Number of turns	58.5 ± 3.5	56.0 ± 1.0	57.5 ± 1.5
Filament diameter (μm)	37.0 ± 0.1	38.5 ± 0.3	38.6 ± 0.2
Lamp current degradation rate (per day)	$2.9 \pm 0.4 \times 10^{-5}$	$2.9 \pm 0.8 \times 10^{-5}$	$4.4 \pm 0.4 \times 10^{-5}$
Light flux degradation rate (per day)	$6.2 \pm 2.1 \times 10^{-5}$	$5.1 \pm 1.5 \times 10^{-5}$	$5.4 \pm 0.9 \times 10^{-5}$
Number of specimens	3	4	3

Second, the rhenium-doped lamps tested in Experiment 4 had fewer turns than the pure tungsten lamps, but the same current degradation rate. If these lamps had the same number of turns and filament diameter, the rhenium-doped lamps would have the lowest current degradation rate. This suggests that the rhenium-doped lamps should last longer.

Third, the rhenium-doped lamps have the lowest light flux degradation rate, which is also indicative of a longer useful lifetime. If the light output from the lamp in a GOES encoder decreases below a certain level, the encoder will stop working correctly. This problem is solved by increasing the operating voltage of the lamp, which increases light output but shortens the lamp's lifetime. With a lower light flux degradation rate, rhenium-doped lamps can be operated at a lower voltage for a longer period of time. This will increase their lifetime to burn out.

As previously shown in Figure 12, the life of a tungsten or thoria-doped lamp can be divided into three phases: burn-in, grain-growth, and reweld. Since the thoria-doped and pure tungsten filaments have a burn-in phase of about equal length, the data in Table 2 indicates that the thoria-doped lamps have the longest grain-growth phase, but the shortest overall lifetime at 3.54 volts. The thoria in the filament slows down grain growth (the longer grain-growth phase), but it also makes the filament more susceptible to failure when a notch etches through the filament (the shorter reweld phase). In the initial processing of thoria-doped filament wire, the thoria is dispersed through out the filament. Thoria does not dissolve in tungsten, so it is dispersed throughout the filament. The thoria usually exists as small crystals at the grain boundaries of the tungsten. Thoria slows down the grain growth process by impeding grain boundary mobility.[9]

Table 3. Statistics for the 5.00 volts lamps test by the Materials Branch. This table excludes data for one lamp which burned-out early because of a low number of turns.

	Tungsten	Tungsten w. 3% Re	Tungsten w. 1% Thoria
Time to burn out (days)	396 ± 104	338 ± 26	279 ± 19
Time to 1st reweld (days)	194 ± 91	174 ± 8	203 ± 16
Number of turns	58.2 ± 2.9	59.0 ± 2.2	56.5 ± 1.5
Filament diameter (μm)	37.6 ± 0.5	38.7 ± 0.9	37.6 ± 0.4
Number of specimens	8	4	3

The data in Table 3 shows that the pure tungsten lamps have the longest lifetime at 5.00 volts. The reason for the shorter lifetimes of the thoria-doped lamps is assumed to be the same for the 5.00 volt lamps as for the 3.54 volt lamps. The shorter lifetimes for rhenium-doped lamps is because of distortions and twisting of the filament. Of the nine rhenium-doped lamps operated at 4.67 or 5.00 volts, five of them developed severe distortions (see Figure 11). All five lamps were GE-218W doped with rhenium. In the initial processing of rhenium-doped filament wire, the rhenium is dissolved in the tungsten. The rhenium inhibits the grain growth process, but also promotes distortion of the filament. According to the literature, it also reduces the strength of the filament.[6] At these voltages, the useful lifetime of the rhenium-doped lamps would be even shorter than indicated because the encoder application of these lamps requires that the filament must remain straight for proper illumination of the photodetectors in the encoder.

Examination of the scanning electron micrographs of 3.54 volt lamps in Figure 14, shows that the average crystal size in the tungsten wire doped with rhenium is smaller than that in the tungsten wire doped with thoria and the undoped tungsten wire. The rhenium does not allow the tungsten to develop into the large crystals as typically seen in pure tungsten. The pure tungsten and thoria-doped filaments have about the same crystal size, even though data presented earlier shows that it takes longer for the thoria-doped filaments to develop into the large crystals. These photographs show that rhenium limits crystal size in a filament, and that thoria only slows down the rate of grain growth.

The scanning electron micrographs shown in Figure 15, reveal some other interesting phenomena. The thoria that was originally dispersed throughout the thoria-doped filament has "migrated" to several turns on either side of the recrystallized region in the center of the filament (see Figure 15a and 15b). A cross-section of the filament shows that the thoria is only on the surface. In the pure tungsten and rhenium-doped filaments, aluminum has "migrated" to the same region as the thoria (see Figure 15c and 15d). Again, cross-sectioning shows the aluminum to be only on the surface. In the production of tungsten and rhenium-doped filament wire, a small amount of an AKS dopant (aluminum, potassium, and silicon) is added to impede grain growth and to promote an interlocking grain structure.[6]

Lifetime Dependence on Operating Voltage

In Reference 2, an analysis of lamp lifetime dependence on voltage was made for several types of lamps. These lamps included lamps manufactured in 1966, 1969 (similar to the lamps in SMS-1, SMS-2, and GOES-1), and the lamps tested in Experiments 1 and 2. The dependence of lamp lifetime, t, on voltage, V, was expressed as follows:

$$t / t_o = (V_o / V)^m \tag{1}$$

and the lamps from 1966 gave $m = 10$, the lamps from 1969 gave $m = 6$, and the lamps from Experiments 1 and 2 gave $m = 5.6$. Updating this number for the GE-218W lamps tested in Experiments 1 and 2 (as well as Experiments 3 and 4) gives $m = 5.4$. Calculating this number for the doped lamps gives $m = 5.7$ for the rhenium-doped lamps, and gives $m = 6.0$ for the thoria-doped lamps. It is interesting to note that the lamps similar to the SMS-1, SMS-2, and GOES-1 encoder lamps and the thoria-doped lamps from Experiment 4 have the same value of m = 6.0. This would support speculations that these earlier lamps from SMS-1, SMS-2, and GOES-1 were doped with thoria, though the thoria may not be the reason for their longer lifetimes. The physical dimensions of these early lamps (their filaments were longer and had more turns) are the likely cause for their longer life.

Lifetime Dependence on Lamp Dimensions

The lifetimes of the lamps in GOES-5 and GOES-6 show that accurate lifetime predictions can be made using the operating voltage as the only independent variable if the physical dimensions of the lamps do not vary. The lamps tested in Experiment 2 and the lamps used on GOES-5 and GOES-6 had little variation with an average of 60 ± 1 turns, and an average filament diameter of $38.1 \pm .7$ µm. This small amount of variation allowed for the accurate predictions mentioned previously. The lamps tested in Experiment 4 had greater variation with an average of 56 ± 3 turns, and an average filament diameter of $38.1 \pm .7$ µm. This increased variation occurred because the filaments in these lamps were brazed to the support post. The brazing material would "short-out" a couple of turns near the post. The lifetime of these lamps, plotted in Figure 16, shows that there is a strong dependence of lamp lifetime on the number of turns in a lamp. The data from these experiments show only a weak dependence on filament diameter.

Original estimates of encoder lamp lifetime to burn out were extrapolated from accelerated life test data on commercial lamps operated at higher voltages.[1] These estimates assumed that the commercial lamps had the same physical dimensions as the flight encoder lamps. However, calculations made from electrical resistance measurements for the commercial lamps produces an estimate of roughly 70 turns per lamp, as compared to the GOES encoder lamps which have only 60. This calculation assumed that both lamps had the same filament diameter.

The commercial version of these lamps were reported to last 5000 hours at 6.3 volts by Baldwin Electronics, Inc. Assuming that operating a 70 turn lamp at 6.3 volts would be similar to operating a 60 turn lamp at 5.4 volts, the power law shown in Equation (1) was used to recalculate the preliminary lifetime predictions (see Figure 17).

Figure 17 shows the actual lifetimes for the GE-218W tungsten lamps tested by the Materials Branch, and the calculated lifetimes from the commercial lamp information using a value of m = 10 (the upper curve). This value was established from lamps operated at higher voltages, where the primary failure mechanism was evaporation of the filament.[1] The middle curve on this graph was calculated for lamps with 70 turns and used an exponent of 5.4, which is the "measured" exponent for the grain growth failure mechanism as a function of voltage. The lower curve was calculated for lamps with 60 turns and also used an exponent of 5.4. Comparing the lower two curves shows the critical dependence of lamp lifetime on the physical dimensions of the lamp, while the upper curve shows a combined effect of the exponent value and number of turns.

CONCLUSIONS

Achieving the Initial Objectives

• Determining lamp aging characteristics as a function of voltage

The lamp aging characteristics as a function of voltage have been determined from this program. The primary failure mechanism in these lamps is associated with grain growth occurring in the filament, not evaporation of the tungsten. The rate of grain growth is a function of voltage (actually temperature), with the rhenium-doped lamps having the slowest rate compared to thoria-doped and pure tungsten lamps. While rhenium inhibits grain growth in the filament, distortion and twisting of the filament at the higher operating voltages gives these lamps a shorter lifetime. At lower voltages this distortion has not been observed, so the rhenium-doped lamps should have the longest useful lifetime. The thoria-doped lamps also have a slower grain growth rate than pure tungsten, but the thoria-doped lamps have a shorter reweld phase. As a result of this shorter reweld phase, the thoria-doped lamps have the shortest overall lifetime.

The electrical current and light output from a lamp vs. time also can be used to examine the aging characteristics of a lamp. The life of a lamp has been described as having three phases (burn-in, grain-growth, and reweld or distortion). The length of these phases strongly depends on operating voltage, number of turns, and filament material.

• Determining the ultimate lamp lifetime as a function of voltage

Lamp lifetime has been shown to follow the power law stated by Equation (1). The exponent in this equation was originally estimated to be about 10. The testing done by the Materials Branch has found this exponent to be 5.4 for pure tungsten lamps, 5.6 for rhenium-doped lamps, and 6.0 for thoria-doped lamps.

• Comparing laboratory results to in-orbit experience

The laboratory results and the in-orbit results for GOES-5 and GOES-6 encoders show no difference in lamp life. The lamps in the GOES-7 have not been operated to date, so no comparison can be made between the encoder lamps and the rhenium-doped lamps tested at GSFC.

• Predicting operational lifetimes for GOES-5, GOES-6, and GOES-7 encoders

As discussed previously, the laboratory results have been successfully used to predict the in-orbit failures of the six lamps in GOES-5 and GOES-6. Three of the predictions for the lamps were within the uncertainty of the prediction; the other three predictions were within one month of the uncertainty of the prediction. Predictions have been made for the GOES-7 encoder lamps.

• Finding operational conditions which will maximize the useful life of a lamp

In determining the best operating conditions for maximum useful life of an encoder lamp, the following three areas were investigated: process control, filament material, and operating voltage. SBRC did regain the process control that must have existed for the lamps manufactured for SMS-1, SMS-2, and GOES-1. The backfilling procedure developed by SBRC did eliminate the water cycling which occurred in the lamps in GOES-2 and GOES-3, but more attention should have been directed to the dimensions of the filament. The data plotted in Figure 16 clearly show a strong dependence of lamp lifetime on the number of turns in a lamp. The lamps used in SMS-1, SMS-2, and GOES-1 had about 70 turns, later encoder lamps had only 55 to 60 turns. Stricter controls should have existed that addressed the required dimensions for these lamps. At constant voltage and wire diameter, a lamp with more turns will last longer (of course, it will also be dimmer). Lifetime predictions could have been made more accurately if the physical dimensions of these lamps had stricter tolerances.

The best filament material for low voltage applications (3.54 volts and lower) was determined to be tungsten with 3% rhenium. This material was used for the encoders lamps in GOES-7, which can operate at below 3.00 volts. The best filament material at higher voltages (4.5 to 5.0 volts) was determined to be GE-218W tungsten. This material was used in GOES-5 and GOES-6 encoders, which operated at these voltages. Testing at GSFC has shown that lamp life can be dramatically increased if the operating voltage is lowered.

An overall evaluation of this program can be made from examining its impact on the final product -- GOES-5, GOES-6, and GOES-7. GOES-5 lasted 46% of its expected mission life, GOES-6 lasted 83% of its expected life, and GOES-7 is expected to exceed its mission life of seven years (it has lasted 4 years to date). Due to encoder lamp problems, the two satellites which initiated this test program (GOES-2 and GOES-3) lasted only 23% and 39% of their respective mission goals.

Instrumentation (lesson learned)

Automation was essential in developing a reliable and revealing long-term test program. The increased sampling rate of lamp current and light output (once a day), along with periodic scans of the light output vs. position along the filament allowed for the direct observation and identification of the failure mechanism in these lamps. The correlation of the rapid decrease in lamp current several days before a reweld event, was made possible only by using data produced by the filament scanning device.

The automation of data acquisition for Experiment 4 has also permitted this test to continue for eight years with very little maintenance. Since this experiment has required very little human intervention, it has been able to continue at a relatively low cost (just the electricity to power the experiment) with no sacrifice of data. Human intervention has only been needed about once a month to transfer data to a computer. Eliminating the taking of data "by hand" has also greatly reduced the error rate in data entry.

Accelerated Testing (lesson learned)

As exemplified by the GOES encoder lamp experience, attention to the details of the physical parameters and the failure mechanisms in a system such as this are essential in order to correctly extrapolate accelerated lifetime data. The original estimates of lamp lifetime assumed that the failure mechanism in the encoder lamps was evaporation of the filament, and that the commercial lamps had the same physical dimensions as the flight encoder lamps. Both of these assumptions caused the predicted lifetimes to be longer than the actual lifetimes observed in-flight. Testing at GSFC determined both that grain growth was the primary failure mechanism and that the number of turns for the flight lamps was less compared to commercial lamps which used accelerated life test data based on an evaporation failure mechanism model. These findings account for the performance of the flight lamps.

The lower curve in Figure 17 shows that if the original predictions had accounted for dimension differences and if grain growth had been identified as a failure mechanism, accurate lifetime predictions could have been made. A lesson learned from this experience is to only put faith in accelerated test results when a complete understanding of the failure mechanisms of the system in question have been established. Even then, accelerated test data should be used with caution.

ACKNOWLEDGEMENTS

Over the past twelve years, there have been many contributors to this lamp study whom the author would like to recognize. This program would not have happened but for the efforts of Walter Viehmann. As a member of the Tiger Team, Mr. Viehmann identified the lamps as the cause of the encoder failures. Mr. Viehmann also successfully developed and applied the technique that was used to predict the in-orbit failures of GOES-1, GOES-5, and GOES-6 encoder lamps. Mr. Viehmann was assisted in developing this technique by Norman Helmold. Mr. Helmold was also instrumental in the design, construction, and maintenance of all four experiments. Mr. Helmold procured all the lamps tested in this program. The efforts of Henning Leidecker at predicting lamp failures in GOES-6 and predicting the expected lifetimes of lamps in GOES-7 have contributed to the continuing success of the program originally established by Mr. Viehmann and Mr. Helmold. The dedicated work of Dr. Leidecker has also allowed for the indentification of the failure processes in these lamps. Dr. Leidecker originally conceived the design, and constructed the prototype model of the filament scanning device. At the start of this program other contributors included Henry Price who made many useful suggestions, John Chandler who assisted in constructing some of the experiments, and Cyrus Butner who also assisted in constructing some of these experiments. The efforts of Timothy Van Sant at operating and improving the filament scanning device have proven invaluable. Mr. Van Sant also helped with many long hours entering data from Experiment 1 into the computer, and digitizing early scan data which were recorded in hardcopy form only. The efforts of many co-op students in the Materials Branch in gathering data from the scanning device allowed for the direct observation of "hot spots" in real time. These students included Roy Vanderhoff, Mark Sarisky, and Stacey Conners. The expertise of Richard Marriott, Bradford Parker, and Sharon Cooper in obtaining scanning electron micrographs have helped in identifying the failure mechanism in these lamps. Rebecca Derro's diligent and expert work has greatly contributed to this report, in supplying the scanning electron micrographs printed in this report. Her measurements of the physical dimensions of the lamps is also appreciated. The cross-sectioning of lamps and filaments by Diane Kolos was quite helpful. The financial support of the GOES project has been greatly appreciated. The software developed for the instrument controllers by Jovian Systems, Inc. has allowed this program to continue almost on its own. The cooperation of R. Roberts (SBRC) and G. Barnett (SBRC) in providing lamps for this study and early lamp data is also greatly appreciated. Lastly, I would like to thank Tom Heslin for his numerous reviews and editorial suggestions in writing this report.

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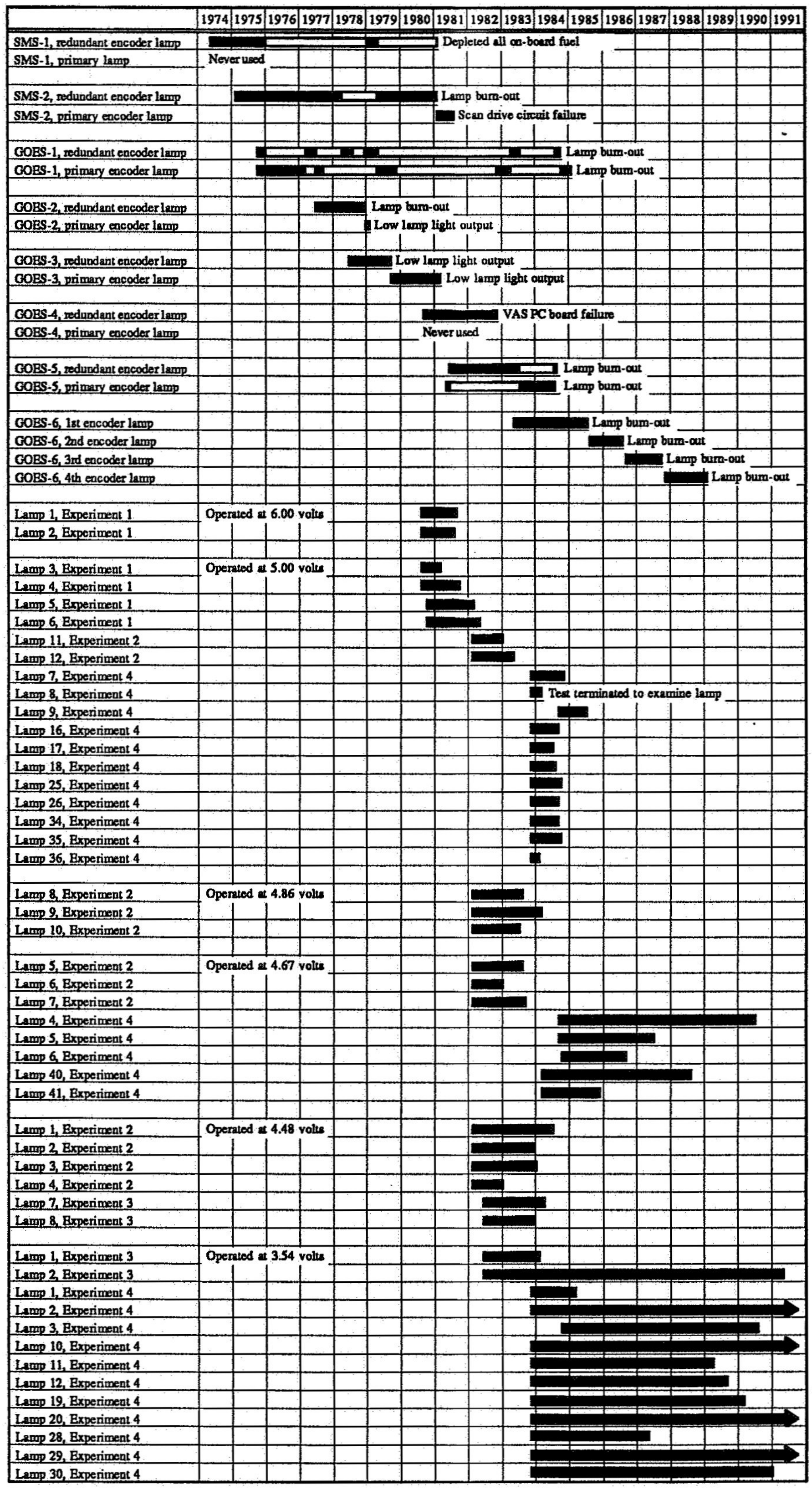


Figure 1. Timechart showing when the encoder lamps in the GOES series and those used for life testing as GSFC were operated. The dark bars represent when the lamps were operated, the clear bars represent when the lamps were on standby.

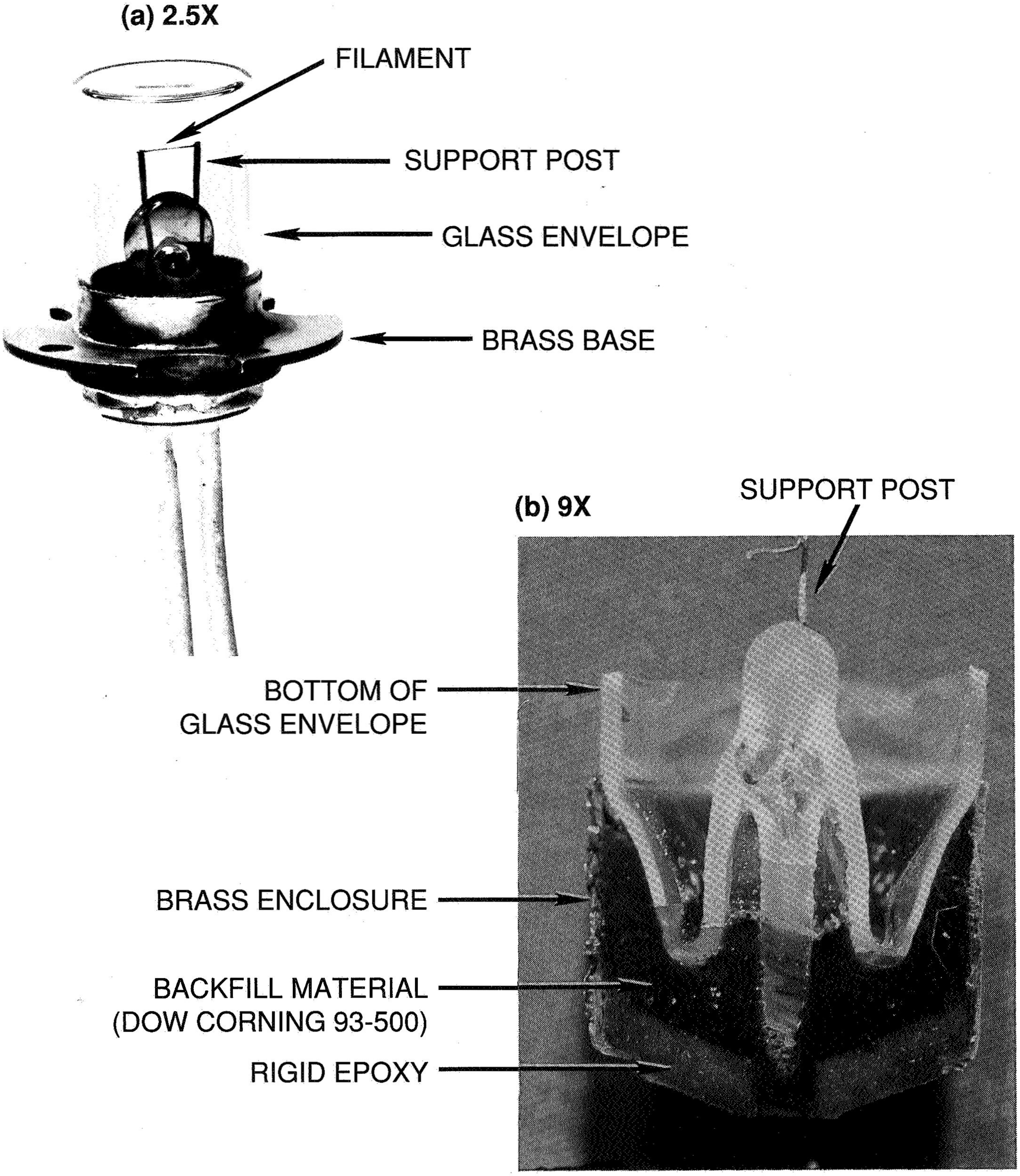


Figure 2. GOES encoder lamp. (a) Photograph of lamp. (b) Cross-section of lamp.

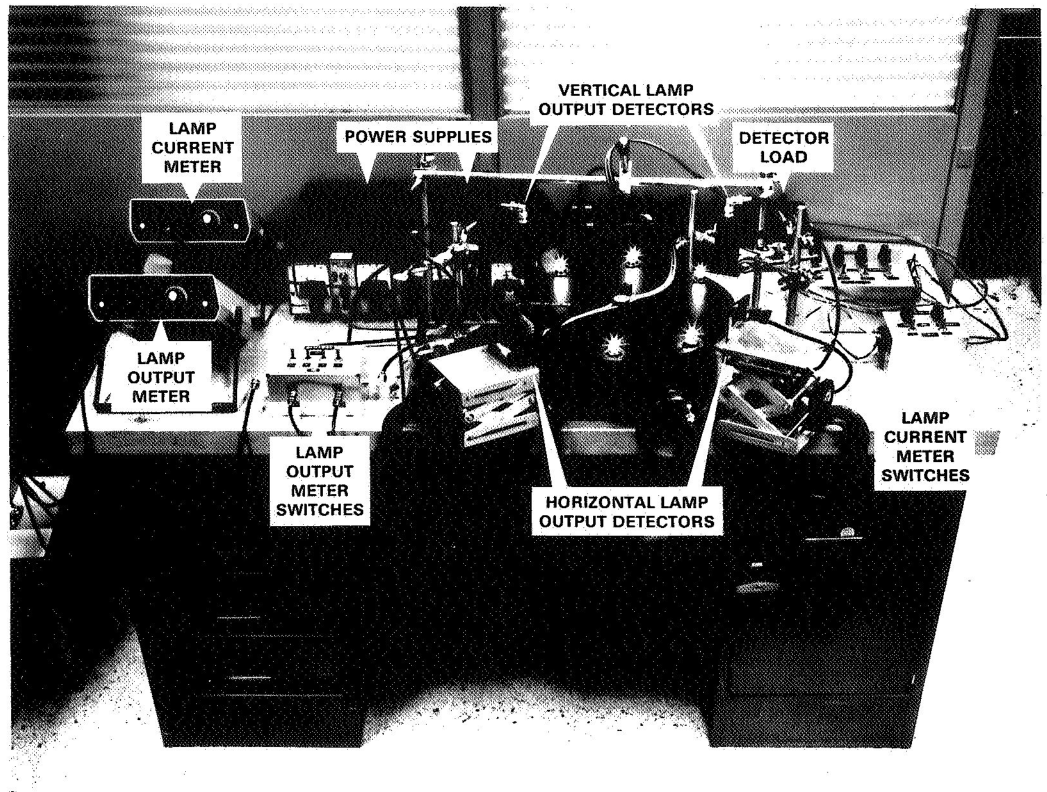


Figure 3. GOES encoder lamp test facility, Experiment 1.

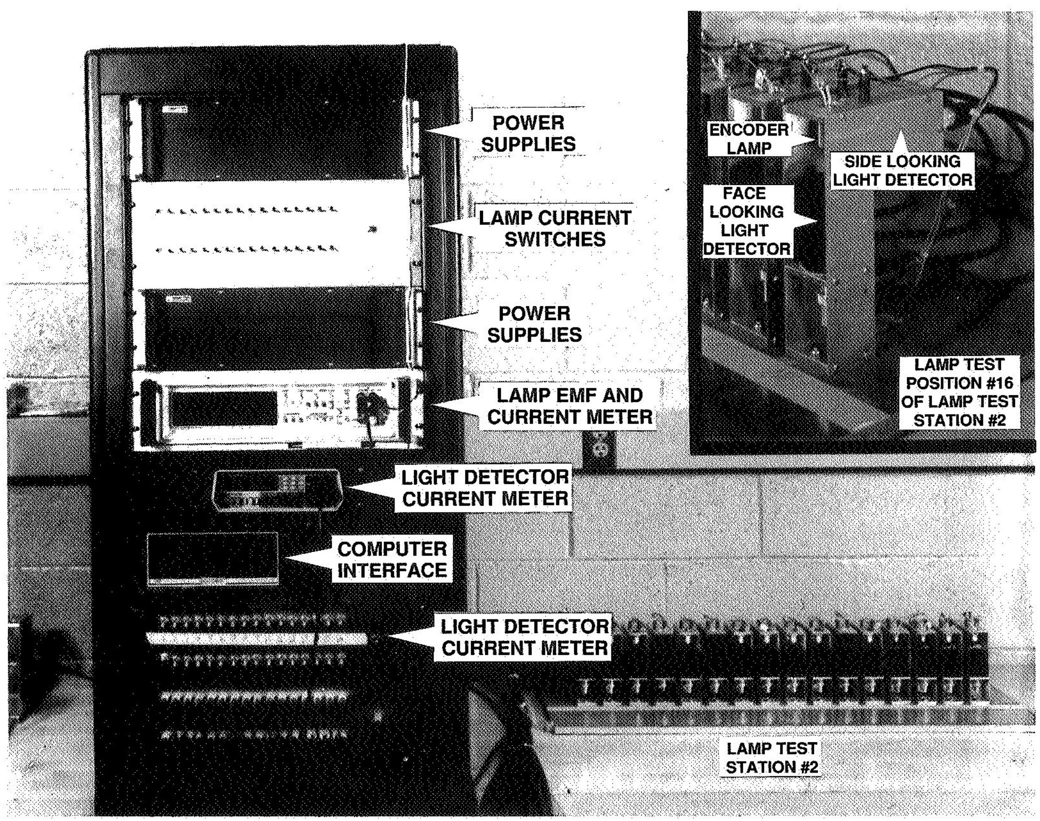


Figure 4. GOES encoder lamp test facility, Experiments 2 and 3.

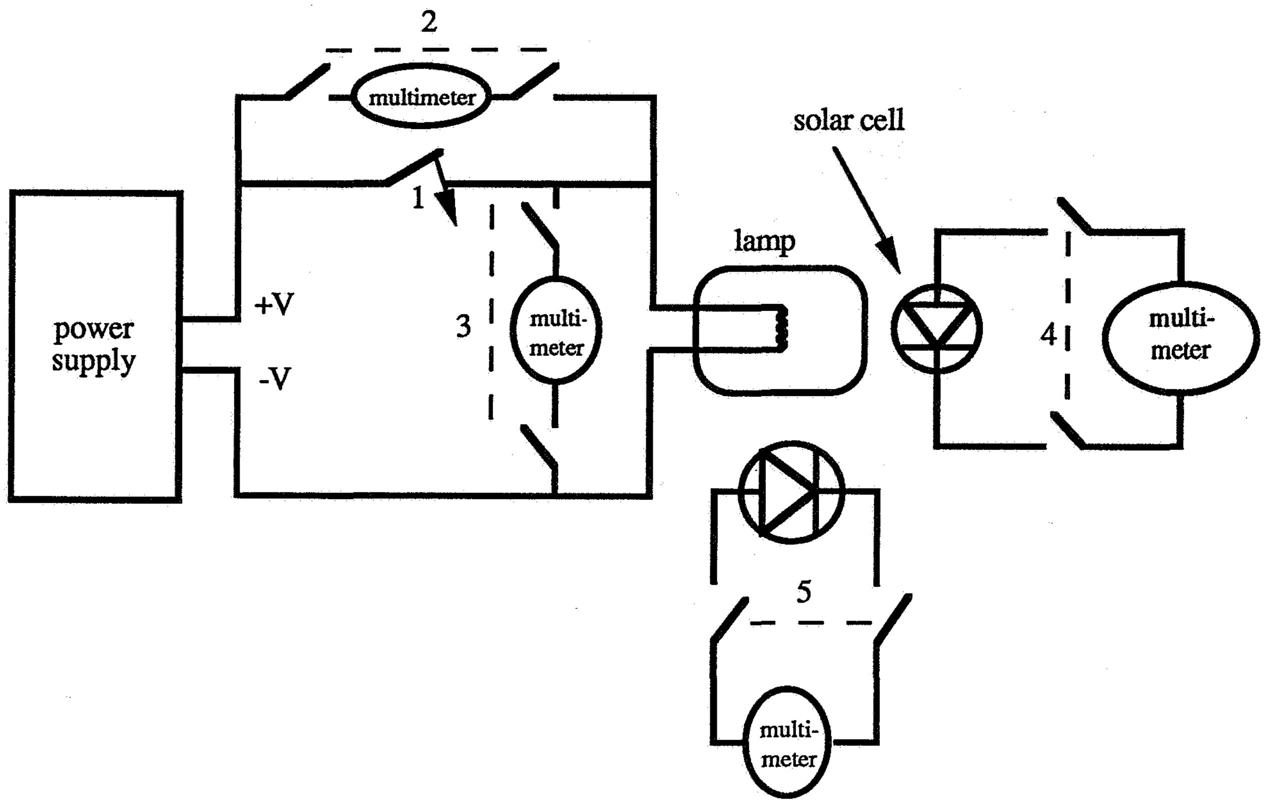


Figure 5. Schematic diagram of a lamp test station from Experiment 4. All switches are located in the Fluke 2205A Switch Controller. To measure lamp voltage, switch 3 is closed. To measure lamp current, switch 2 is closed and switch 1 is opened. To measure light output (solar cell current), either switch 4 or 5 is closed.

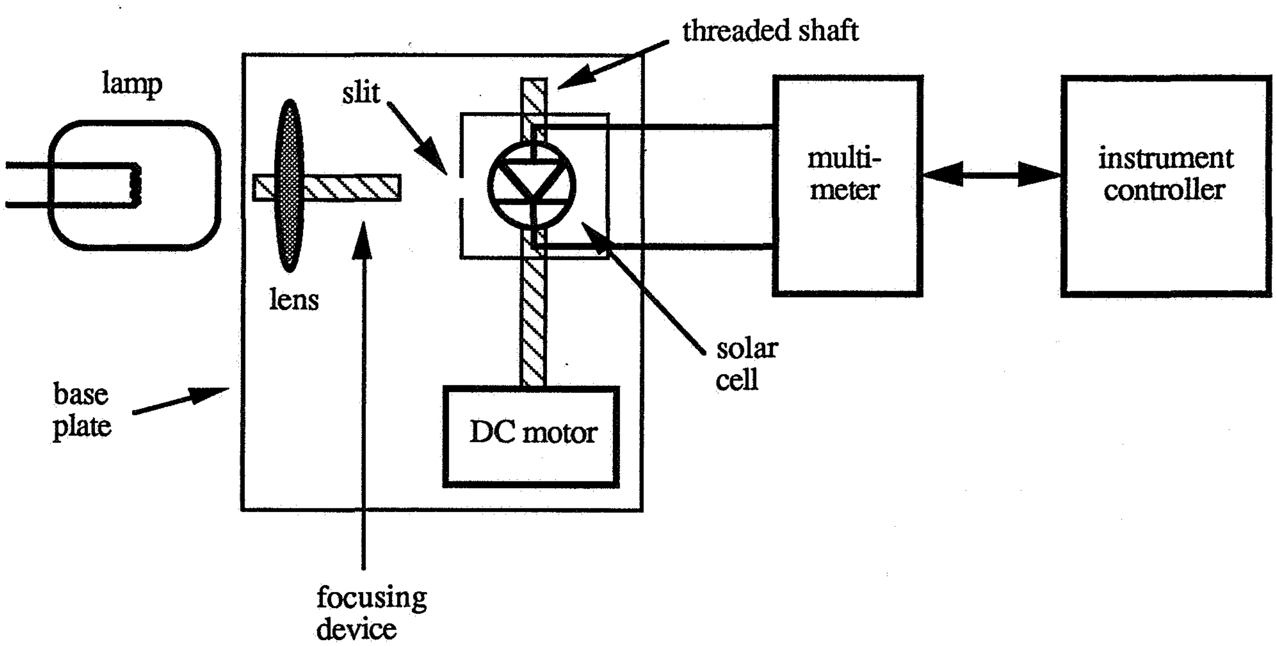


Figure 6. Schematic diagram of the filament scanning device. The lens projects an image of the lamp filament onto the solar cell, which has a slit in front of it. The DC motor drives the solar cell across the image on a threaded shaft.

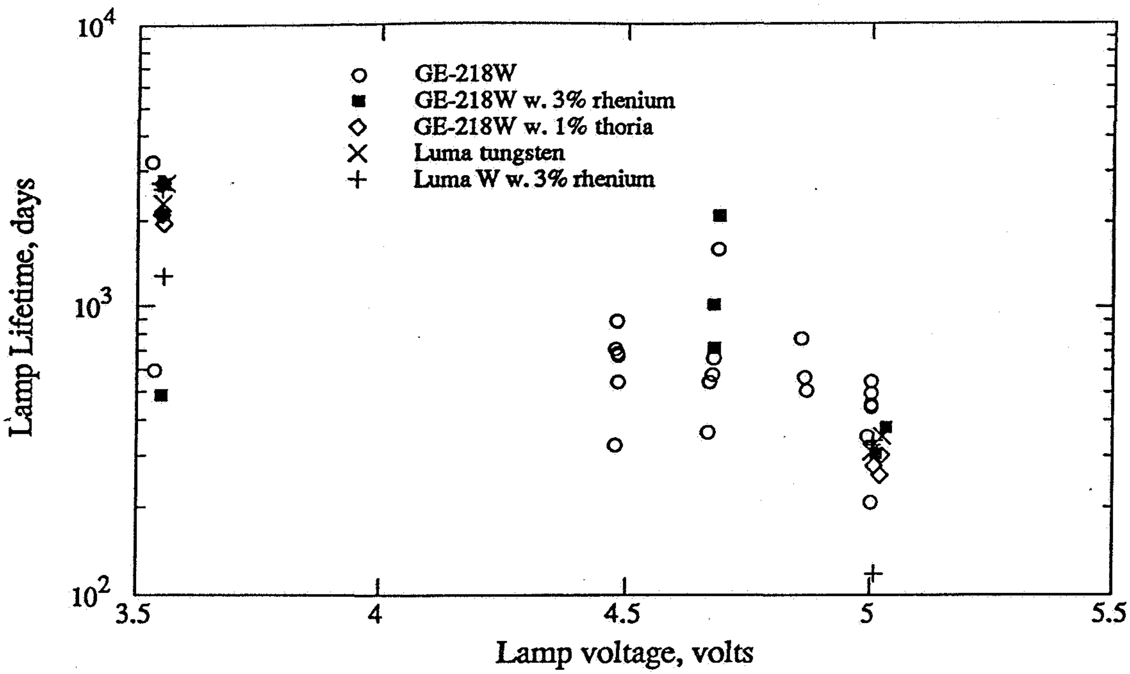


Figure 7. Plot of lamp lifetime to burn out for lamps tested by the Materials Branch. Four of the lamps, operating at 3.54 volts, whose data are plotted on this graph are still running after 2700 days.

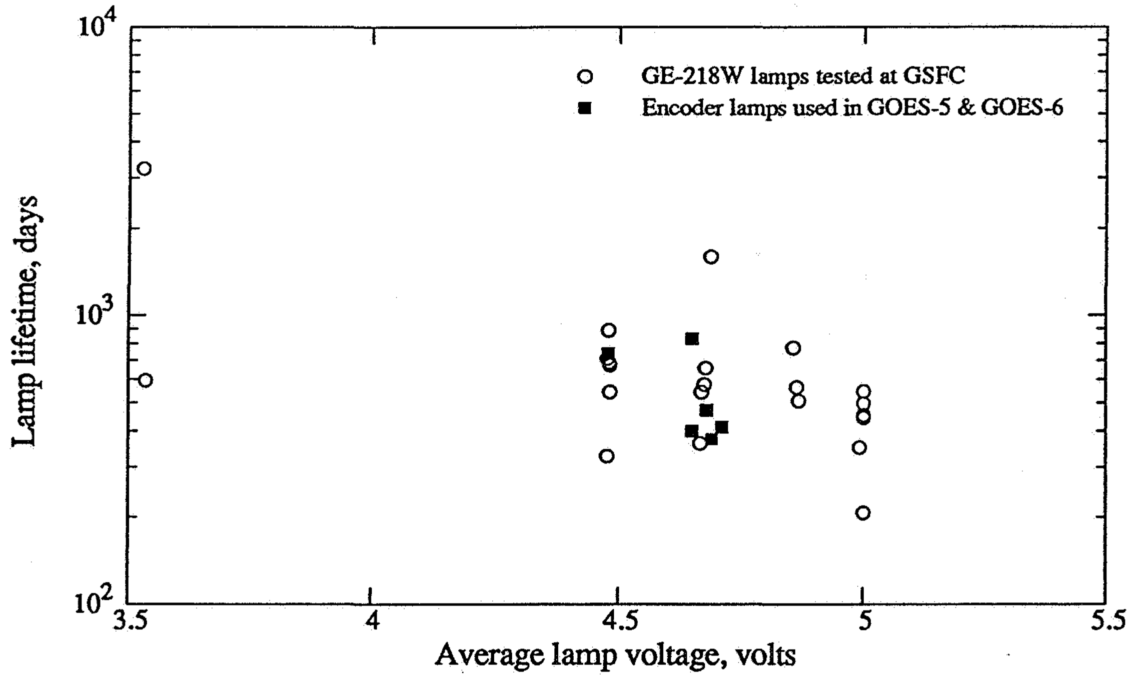


Figure 8. Comparison of the lifetimes of GOES-5 and GOES-6 flight lamps with the lamps tested at GSFC.

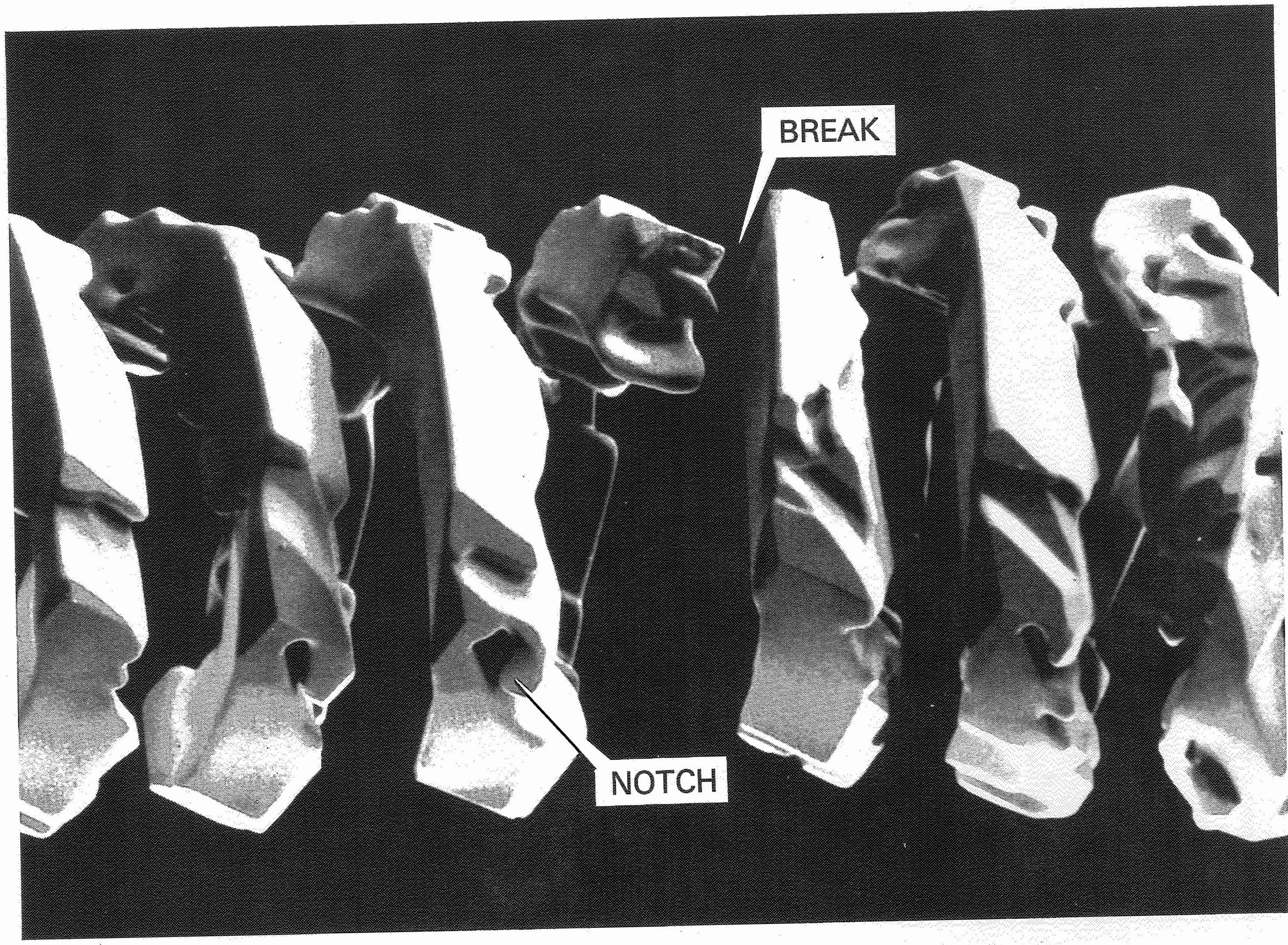


Figure 9. Scaning Electron Micrograph showing crystallized filament with notches developing.

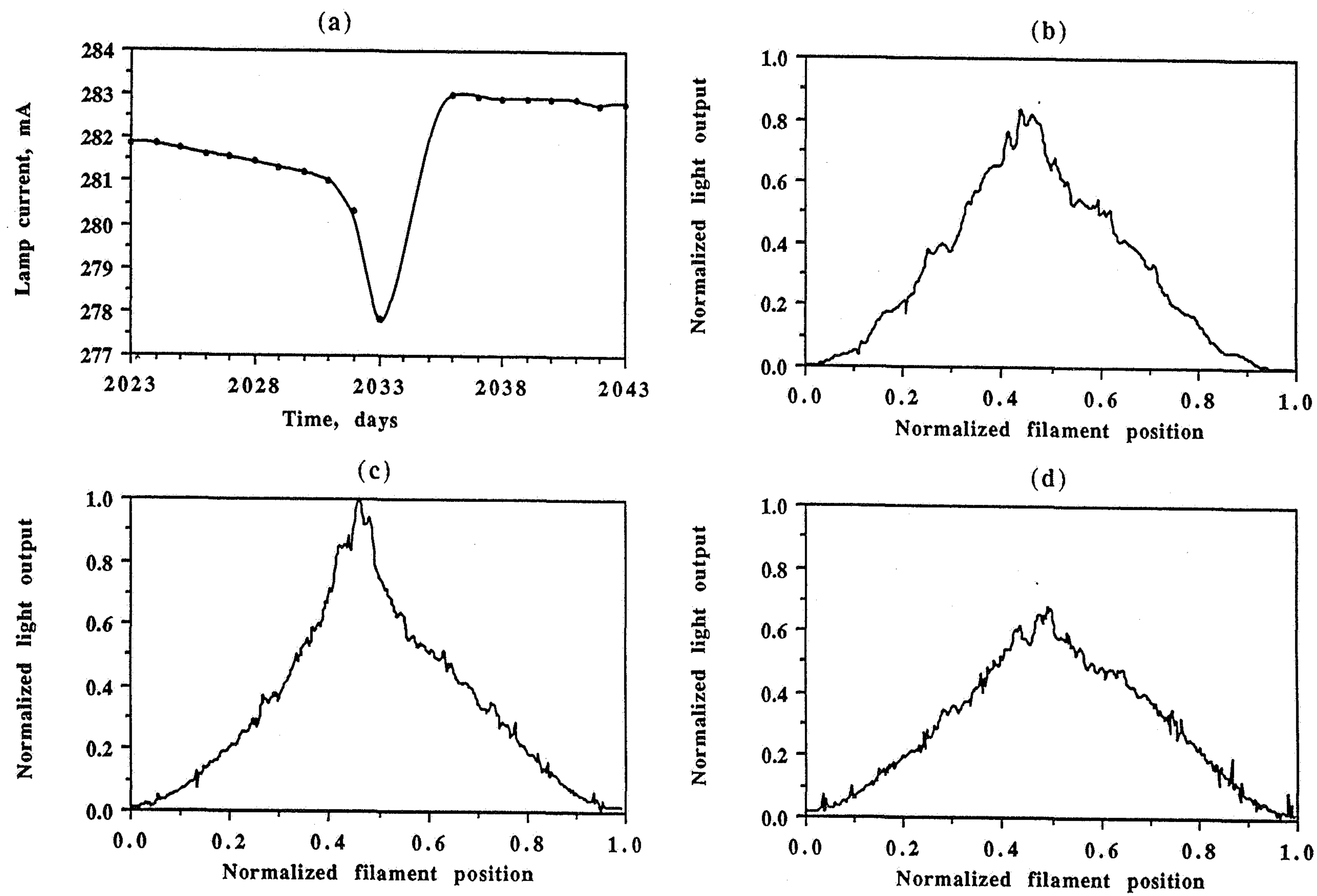


Figure 10. These graphs shown what happens to the lamp current and light output before, during, and after a reweld event. (a) Lamp current vs. days of operations for Lamp #12 of Experiment #4. The reweld event occurred on day 2033. (b) Light output vs. filament location on day 2031 (two days before the reweld). (c) Light output vs. filament location on day 2033 (reweld occurred on this day). (d) Light output vs. filament location on day 2035 (two days after the reweld). The scanning device was not moved during this event, so that the light output could be compared between scans.

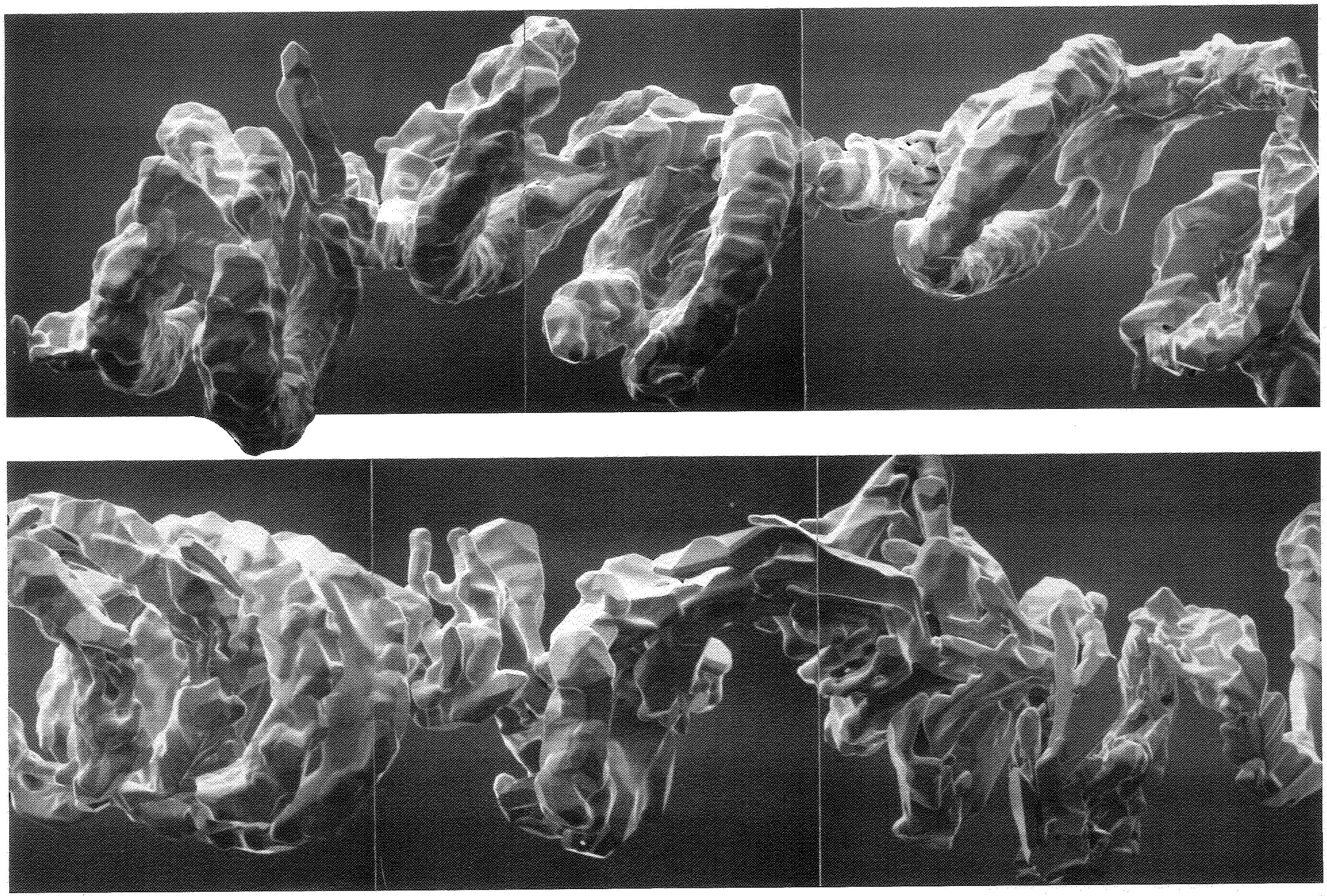


Figure 11. Rhenium-doped filament showing severe distortions.

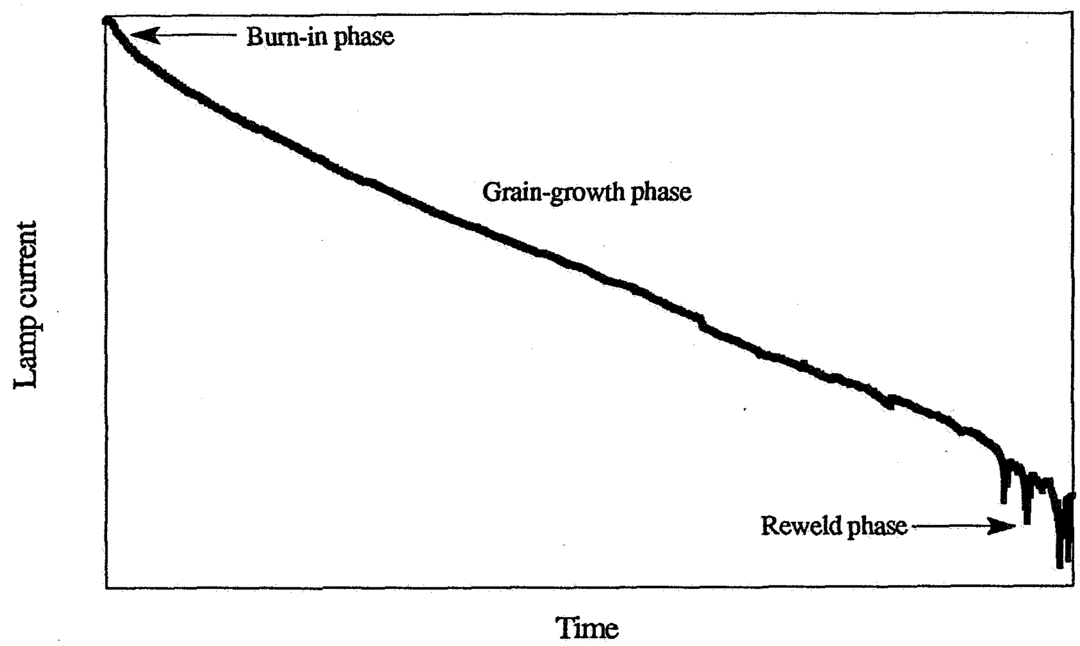


Figure 12. Plot showing the three phases with occur during the lifetime of a typical pure tungsten or thoria-doped lamp operated at constant voltage.

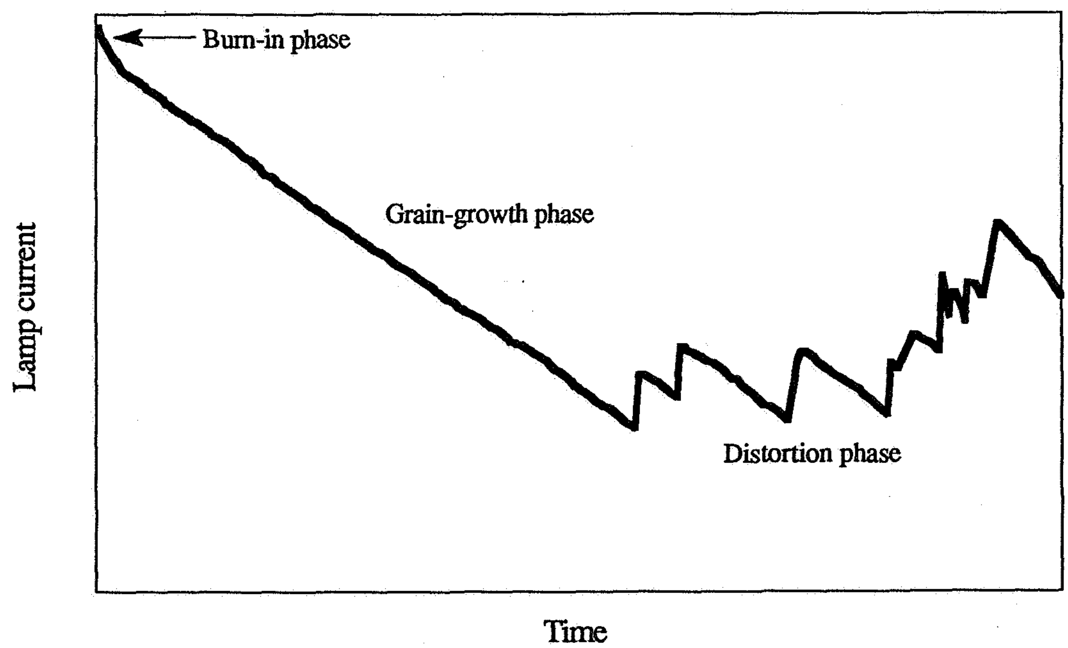
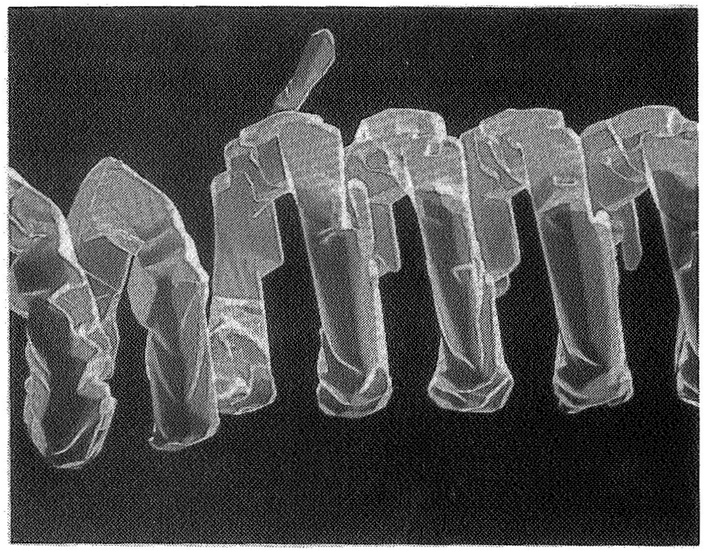
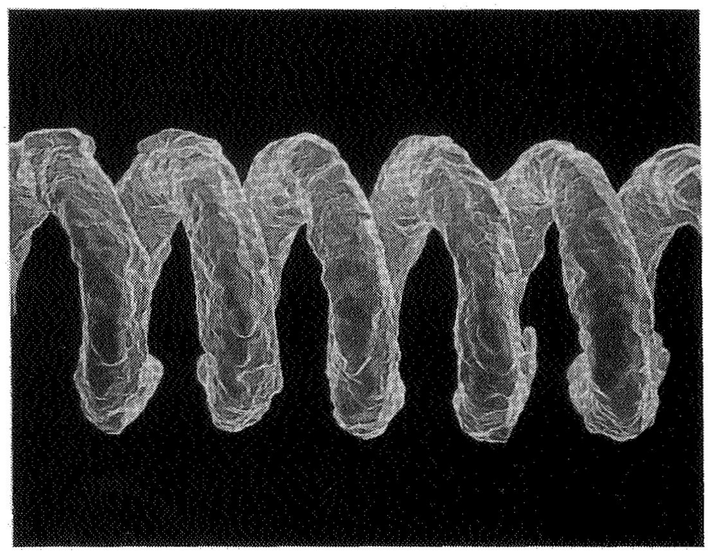


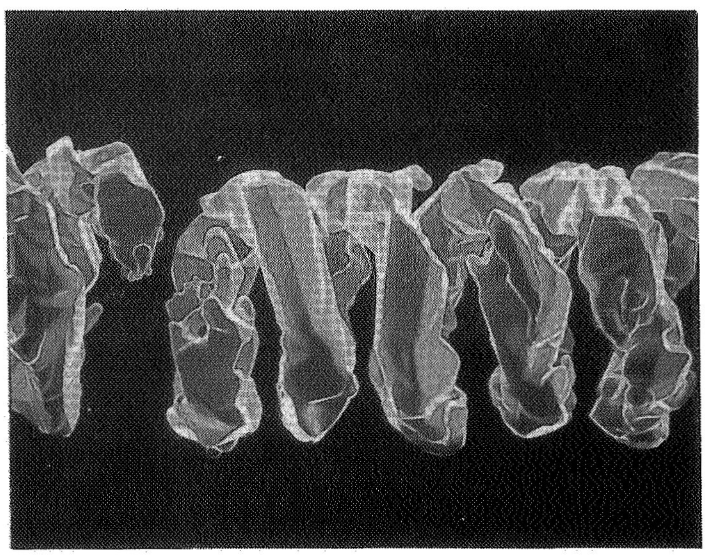
Figure 13. Plot showing the three phases with occur during the lifetime of a typical rhenium-doped lamp operated at constant voltage.



(a) GE-218W (500X)

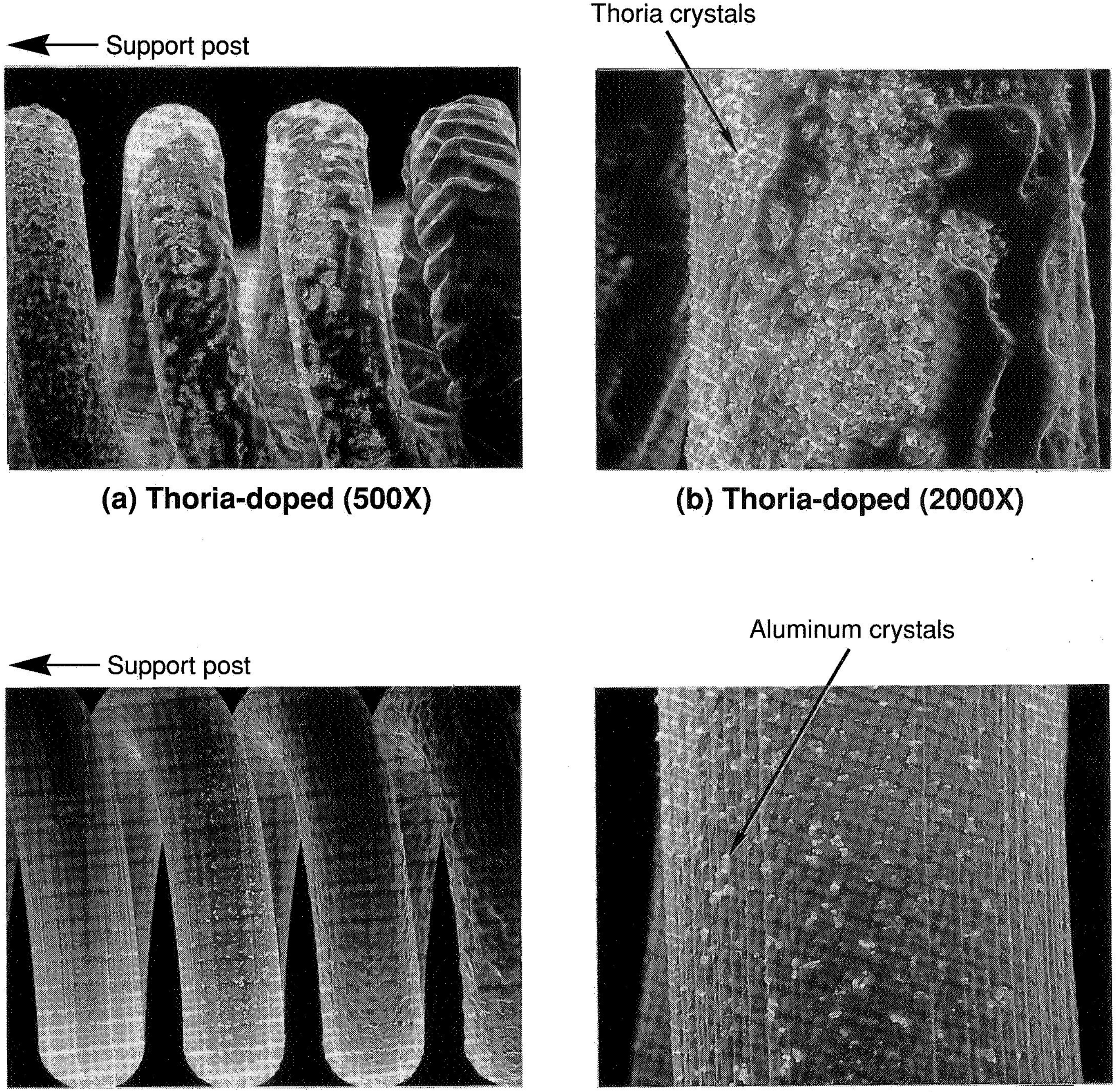


(b) Rhenium-doped (500X)



(c) Thoria-doped (500X)

Figure 14. Crystal development in various lamp filaments for comparable operating times and parameters. (a) GE-218W tungsten wire. (b) GE-218W with 3% rhenium. (c) GE-218W with 1% thoria.



(a) Thoria-doped (500X) **(b) Thoria-doped (2000X)**

(c) Rhenium-doped (500X) **(d) Rhenium-doped (2000X)**

Figure 15. Scanning Electron Micrographs showing migration of aluminum and thoria. The migration of aluminum occurred in pure tungsten and rhenium-doped lamps. The support post for the filament is to the left of the micrograph.

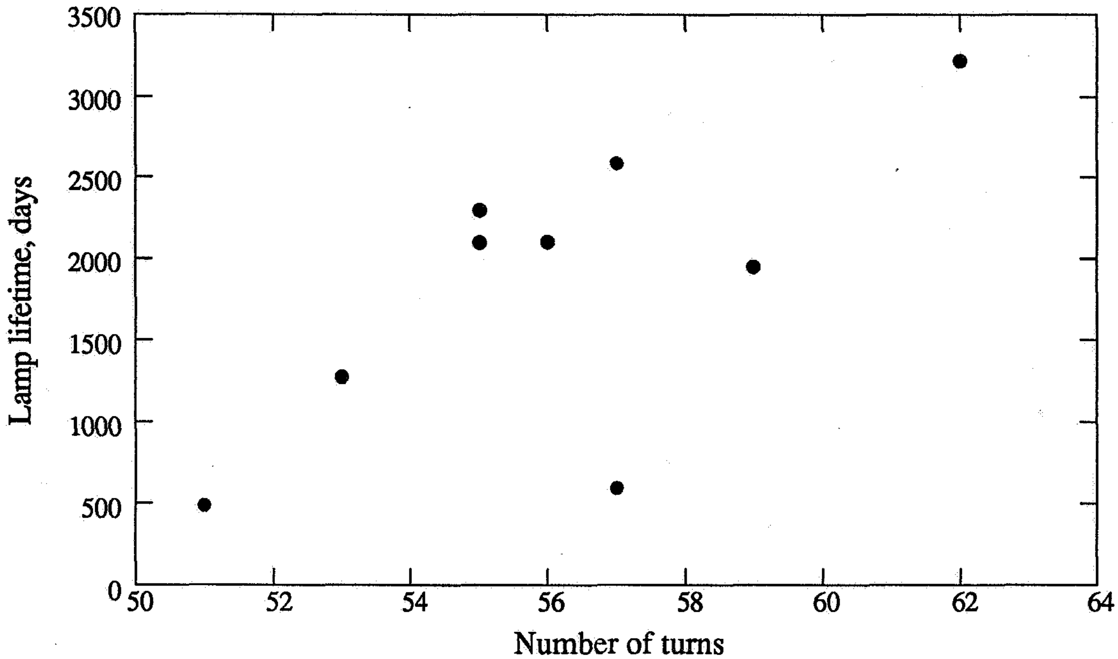


Figure 16. Lamp lifetime vs. number of turns for the 3.54 volt lamps tested by the Materials Branch.

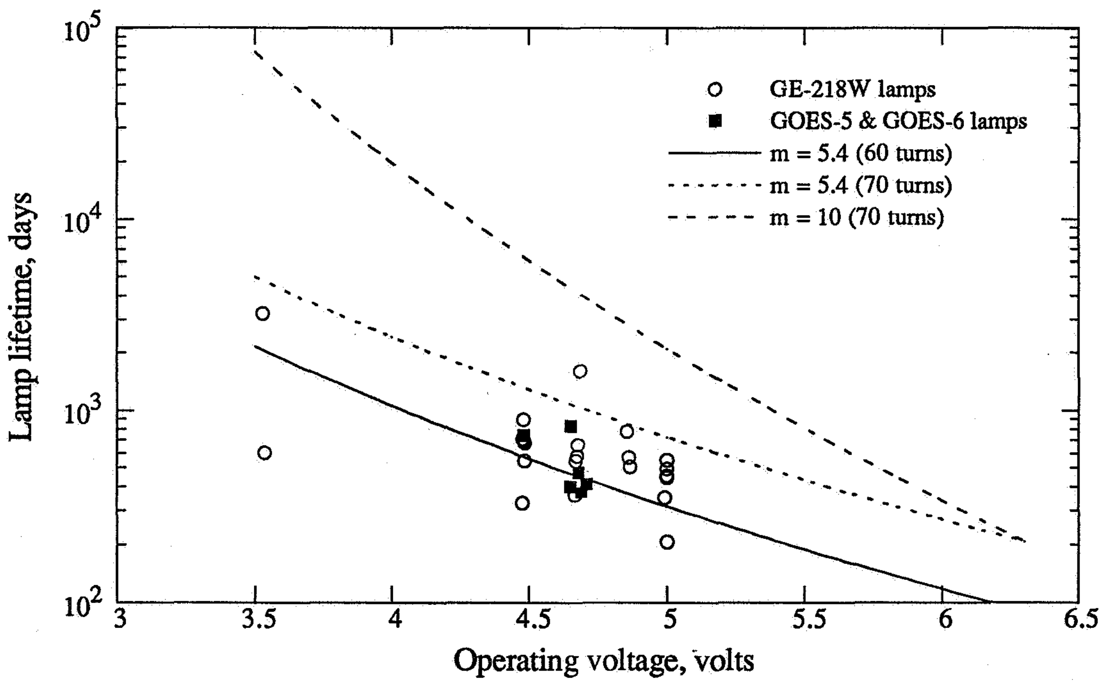


Figure 17. Plot showing lamp lifetime vs. operating voltage for the GE-218W lamps tested at GSFC and the encoders lamps used in GOES-5 and GOES-6. The three curves show lifetime dependence on operating voltage and number of turns using the power law given in Equation 1.

APPENDIX

Data from all four GOES encoder lamp life tests conducted by the Materials Branch of the Goddard Space Flight Center

SBRC part number: none
Filament material: GE-218W
Filament diameter: 37.1 μm
Filament length: 4.723 mm
Number of turns: 74
Post contact technique: welded
Operating voltage: 6.00 volts
Burn-in time: 21 days

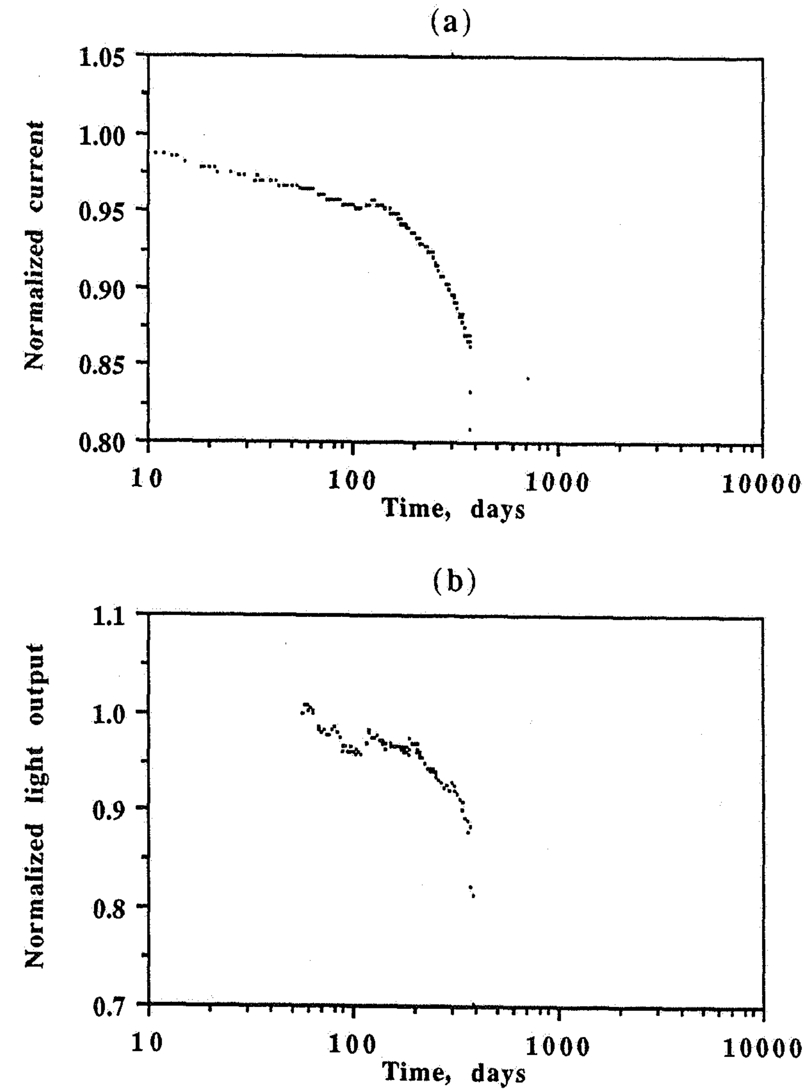


Figure A1. Lamp #1 of Experiment #1. This lamp burned-out after 393 days of operation. No pre-life test characterization was performed on this lamp. The 21 day burn in for this lamp was at 6.00 volts. This lamp would have failed the burn in test (1.53% decrease in current). The envelope darkened during the life test, showing signs of a micro-leak and the "water cycle" in this lamp. (a) Lamp current vs. days of operation. (b) Lamp light output vs. days of operation.

SBRC part number: none
Filament material: GE-218W
Filament diameter: 37.5 µm
Filament length: 4.486 mm
Number of turns: 74
Post contact technique: welded
Operating voltage: 6.00 volts
Burn-in time: 21 days

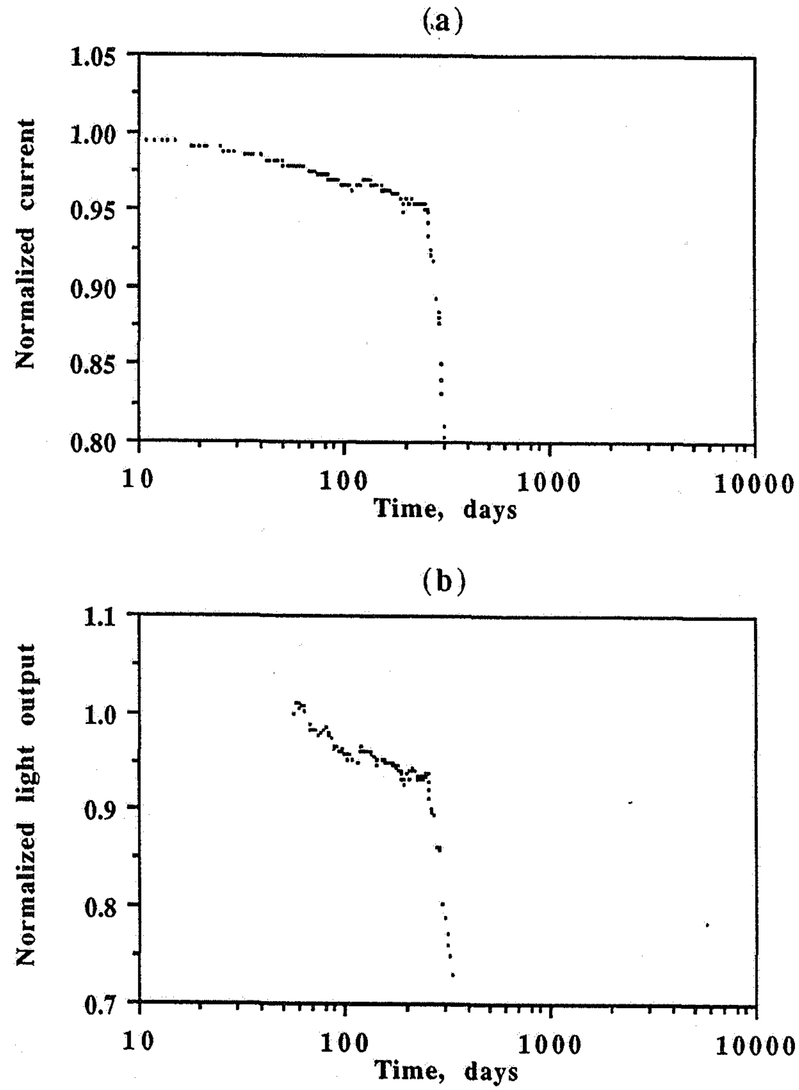


Figure A2. Lamp #2 of Experiment #1. This lamp burned-out after 361 days of operation. No pre-life test characterization was performed on this lamp. The 21 day burn in for this lamp was at 6.00 volts. This lamp would have passed the burn in test (0.31% decrease in current). The envelope darkened during the life test, showing signs of a micro-leak and the "water cycle" in this lamp. (a) Lamp current vs. days of operation. (b) Lamp light output vs. days of operation.

SBRC part number: none
Filament material: GE-218W
Filament diameter: 38.5 µm
Filament length: 3.586 mm
Number of turns: 58
Post contact technique: welded
Operating voltage: 5.00 volts
Burn-in time: 21 days

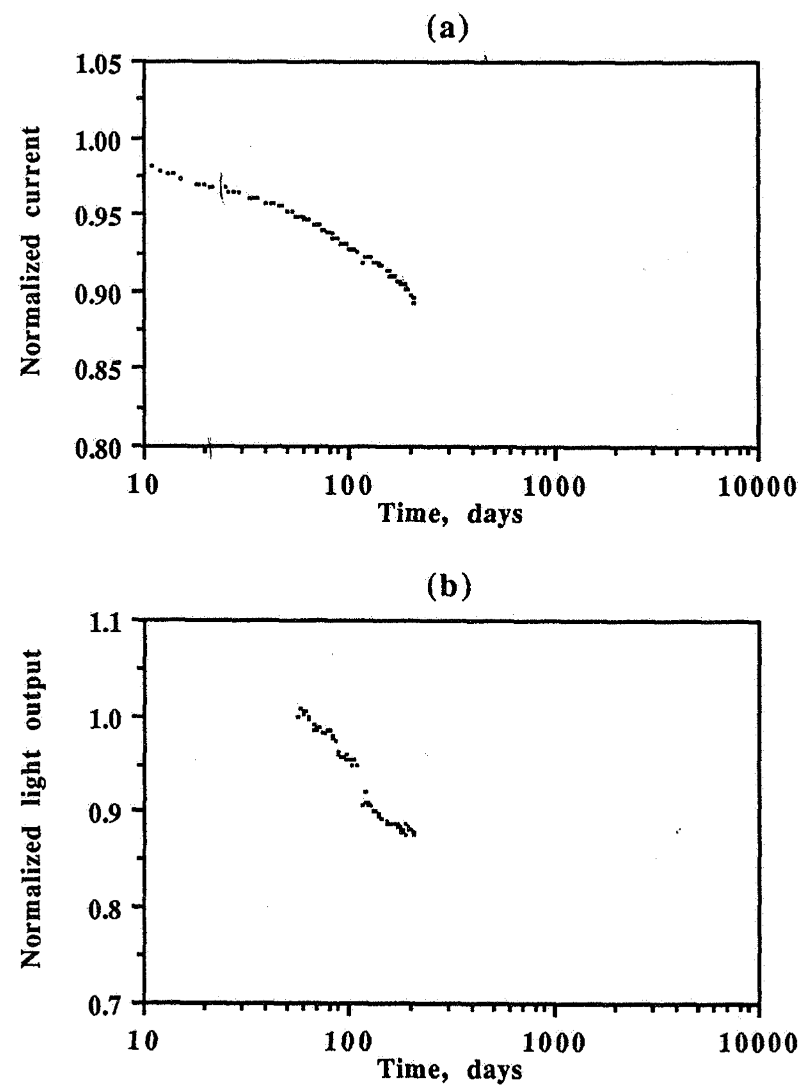


Figure A3. Lamp #3 of Experiment #1. This lamp burned-out after 207 days of operation. No pre-life test characterization was performed on this lamp. This lamp would have failed the burn in test (2.70% decrease in current). (a) Lamp current vs. days of operation. (b) Lamp light output vs. days of operation.

SBRC part number: none
Filament material: GE-218W
Filament diameter: 37.7 μm
Filament length: 3.593 mm
Number of turns: 61
Post contact technique: welded
Operating voltage: 5.00 volts
Burn-in time: 21 days

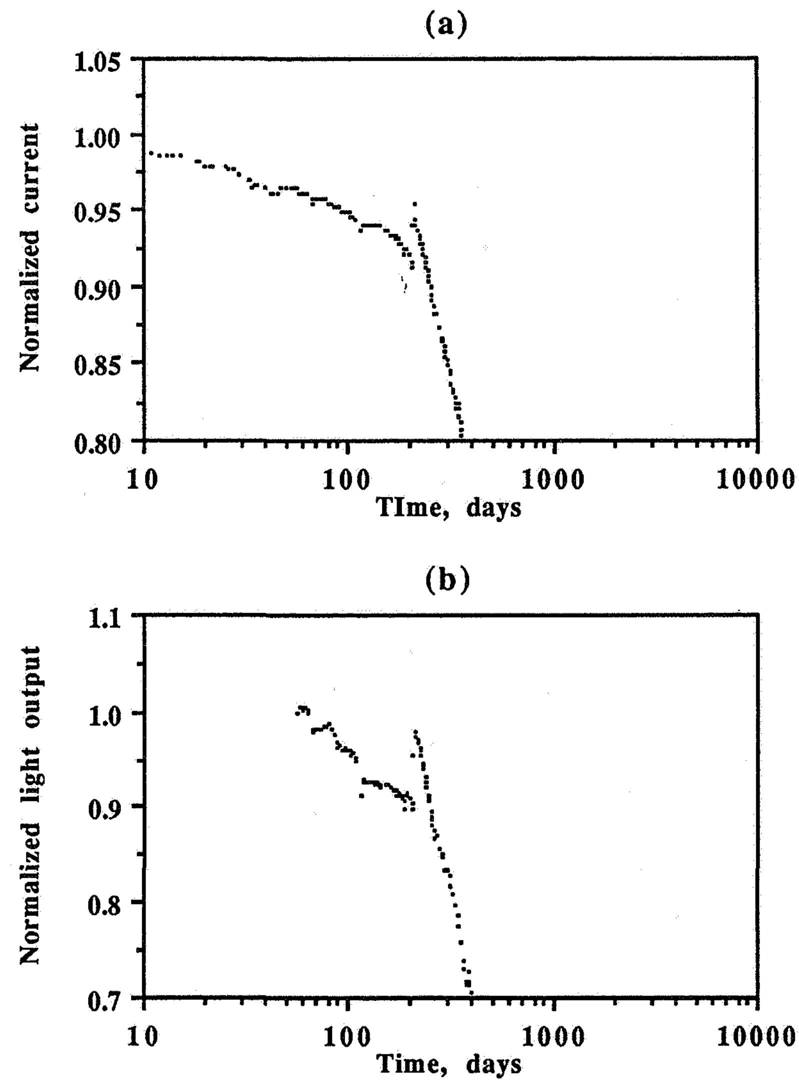


Figure A4. Lamp #4 of Experiment #1. This lamp burned-out after 445 days of operation. No pre-life test characterization was performed on this lamp. This lamp would have passed the burn in test (0.92% decrease in current). The envelope darkened during the life test, showing signs of a micro-leak and the "water cycle" in this lamp. (a) Lamp current vs. days of operation. (b) Lamp light output vs. days of operation.

SBRC part number: none
Filament material: GE-218W
Filament diameter: 37.5 µm
Filament length: 3.529 mm
Number of turns: 59
Post contact technique: welded
Operating voltage: 5.00 volts
Burn-in time: 21 days

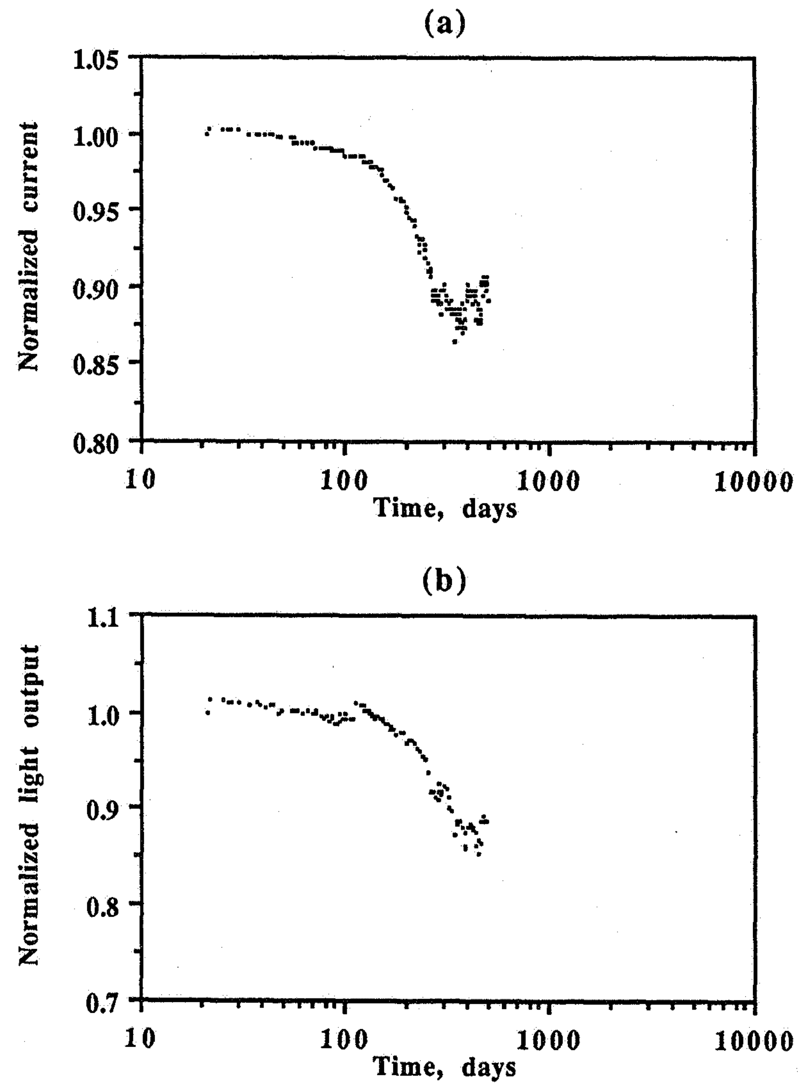


Figure A5. Lamp #5 of Experiment #1. This lamp burned-out after 496 days of operation. No pre-life test characterization was performed on this lamp. This lamp would have passed the burn in test (0.61% decrease in current). (a) Lamp current vs. days of operation. (b) Lamp light output vs. days of operation.

SBRC part number: none
Filament material: GE-218W
Filament diamter: not measured
Filament length: not measured
Number of turns: not measured
Post contact technique: welded
Operating voltage: 5.00 volts
Burn-in time: 21 days

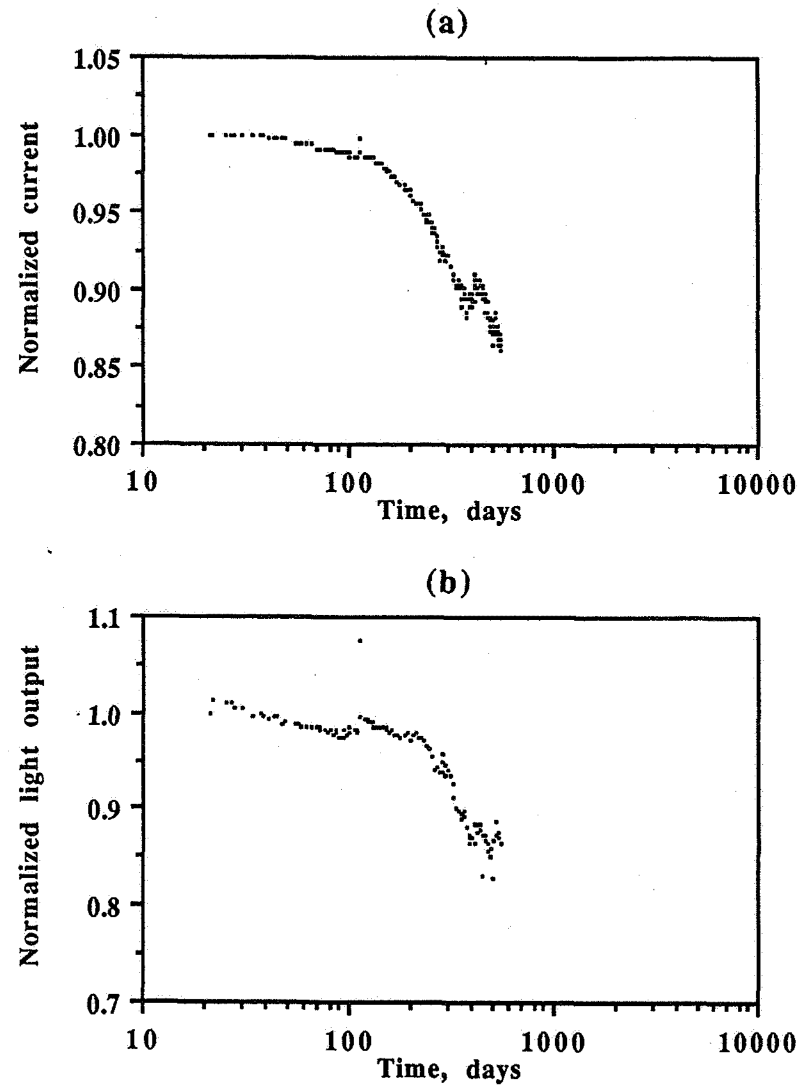
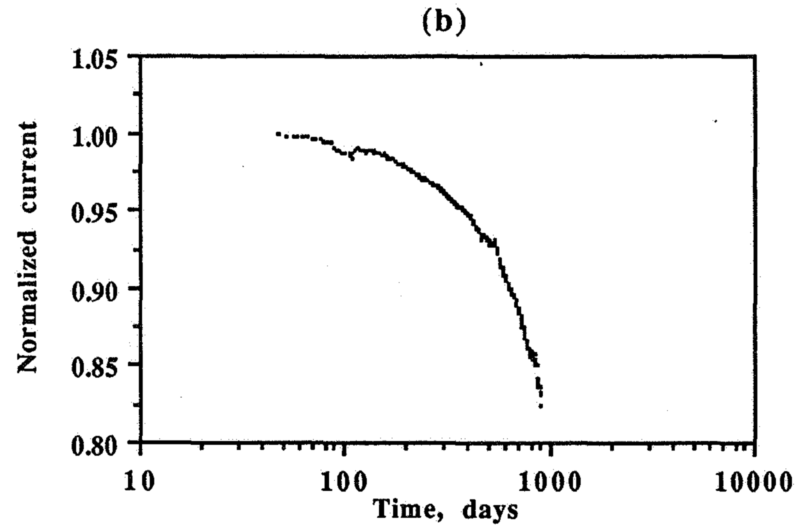
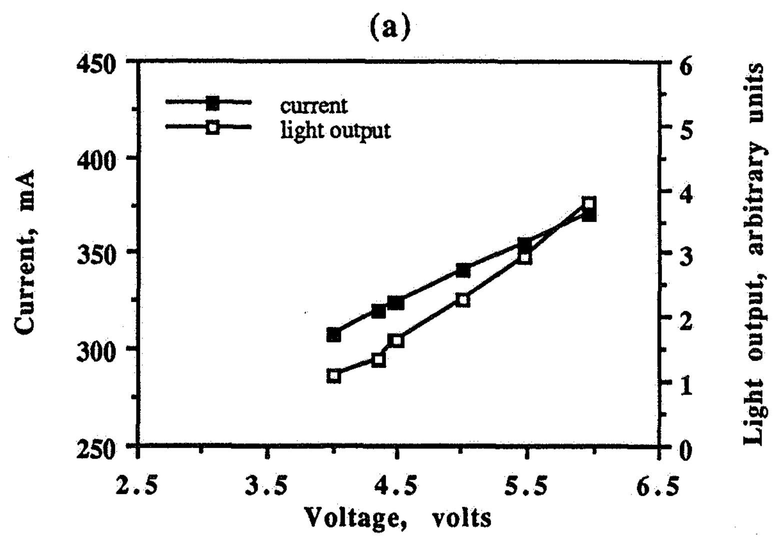


Figure A6. Lamp #6 of Experiment #1. This lamp burned-out after 549 days of operation. No pre-life test characterization was performed on this lamp. This lamp would have passed the burn in test (0.52% decrease in current). (a) Lamp current vs. days of operation. (b) Lamp light output vs. days of operation.

SBRC part number: 1-14-9 (93057)
Filament material: GE-218W
Filament diameter: 39.1 µm
Filament length: 3.837 mm
Number of turns: 60
Post contact technique: welded
Operating voltage: 4.480 volts +0.007,-0.035
Burn-in time: 21 days





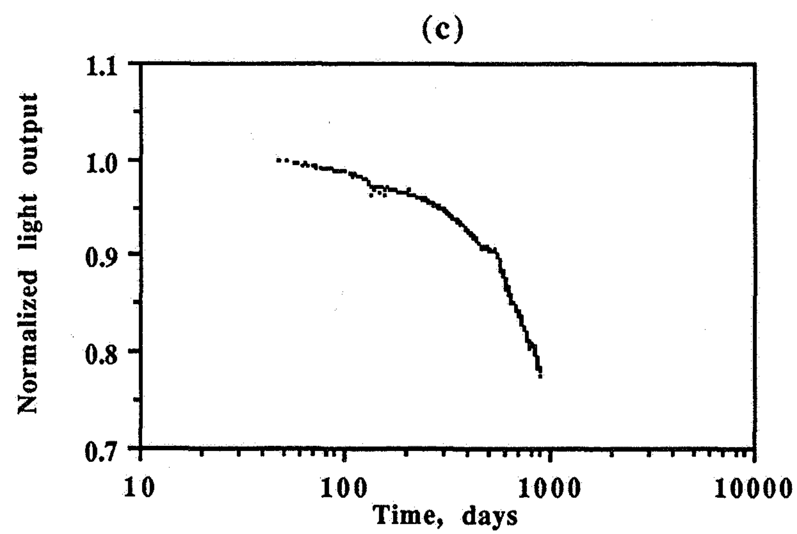


Figure A7. Lamp #1 of Experiment #2. This lamp burned-out after 890 days of operation. This lamp would have passed the burn in test (0.83% decrease in current). This lamp came from the flight lot for GOES-5 and GOES-6. (a) Pre-life test characterization of the lamp. Lamp light output and current vs. voltage. (b) Lamp current vs. days of operation. (c) Lamp light output vs. days of operation.

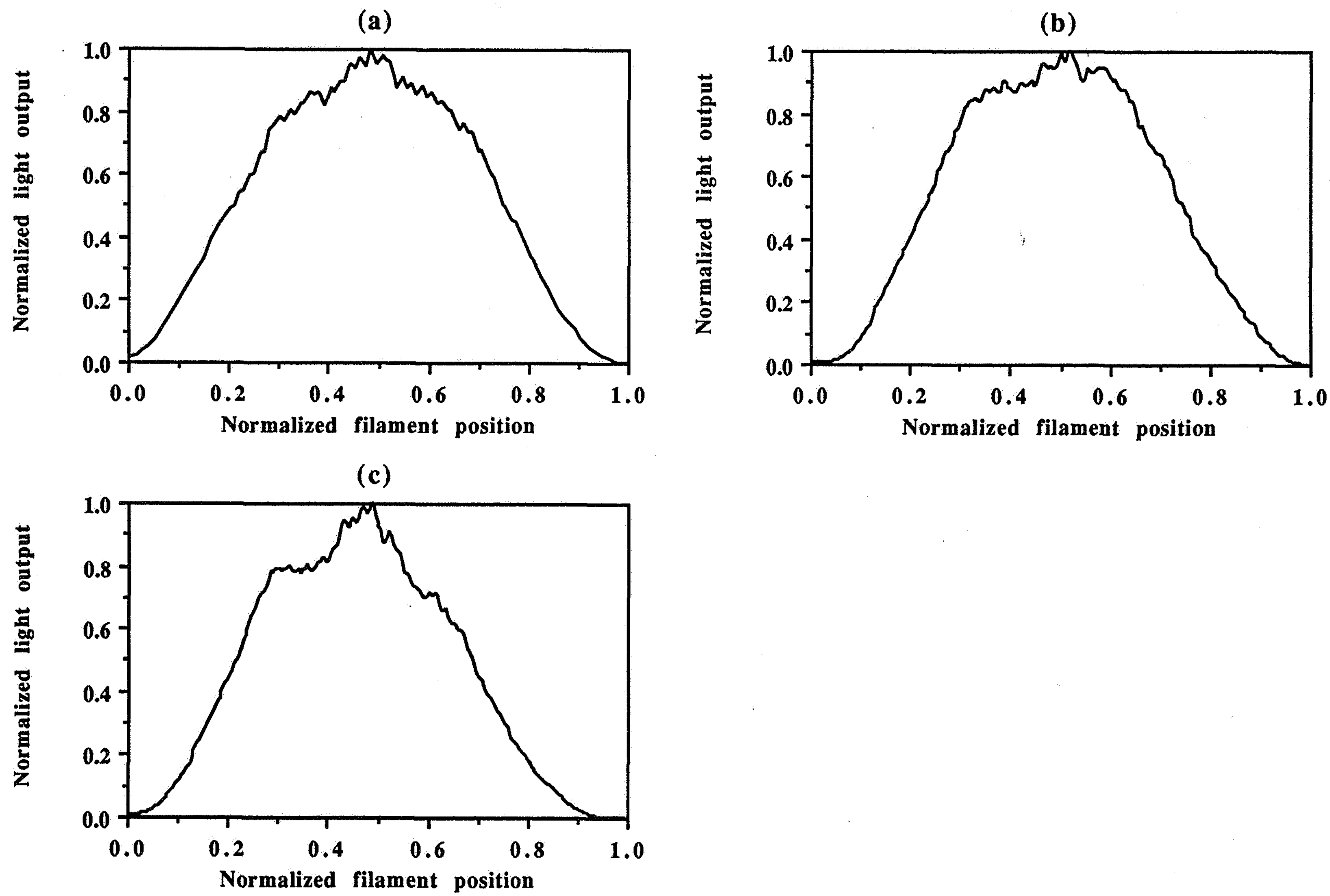


Figure A8. Lamp #1 of Experiment #2. These graphs show the light output from the lamp as a function of location along the filament. This lamp failed at turn 33 from the left. (a) 663 days of operation. (b) 741 days of operation. (c) 846 days operation.

SBRC part number: 7-14-9 (93055)
Filament material: GE-218W
Filament diameter: 38.3 µm
Filament length: 3.772 mm
Number of turns: 61
Post contact technique: welded
Operating voltage: 4.481 volts +0.004,-0.014
Burn-in time: 21 days

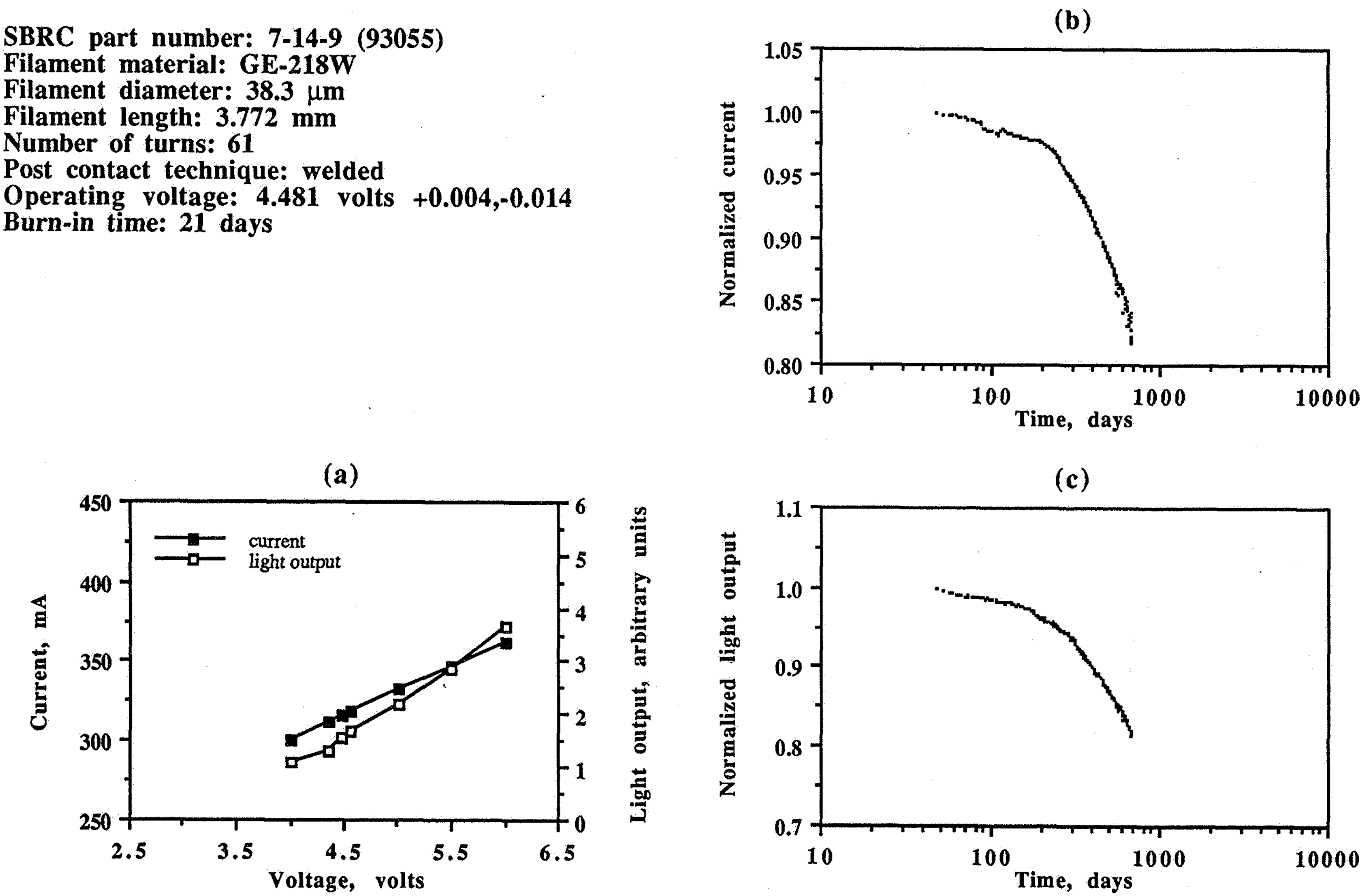


Figure A9. Lamp #2 of Experiment #2. This lamp burned-out after 691 days of operation. This lamp would have failed the burn in test (1.11% decrease in current). This lamp came from the flight lot for GOES-5 and GOES-6. (a) Pre-life test characterization of the lamp. Lamp light output and current vs. voltage. (b) Lamp current vs. days of operation. (c) Lamp light output vs. days of operation.

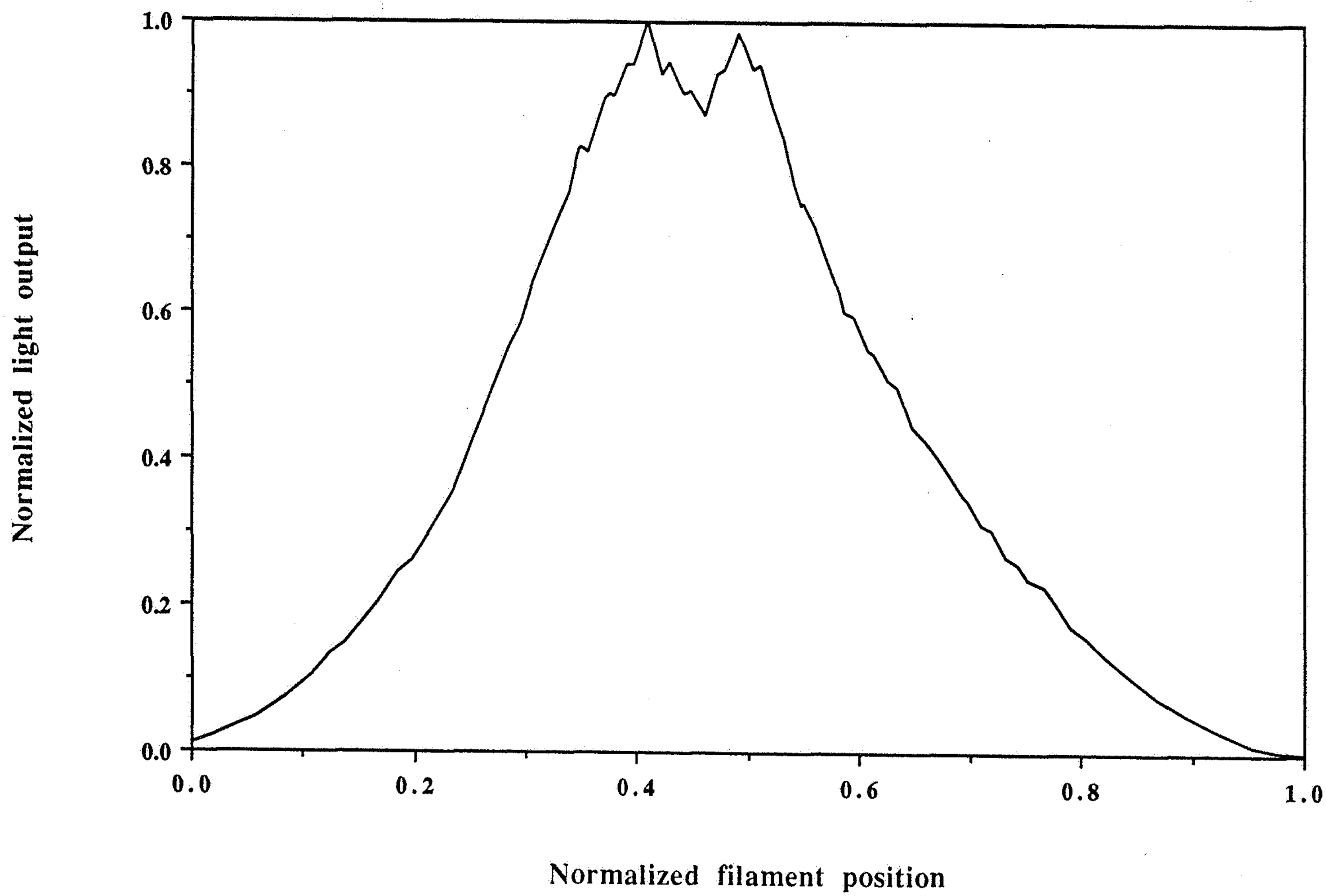
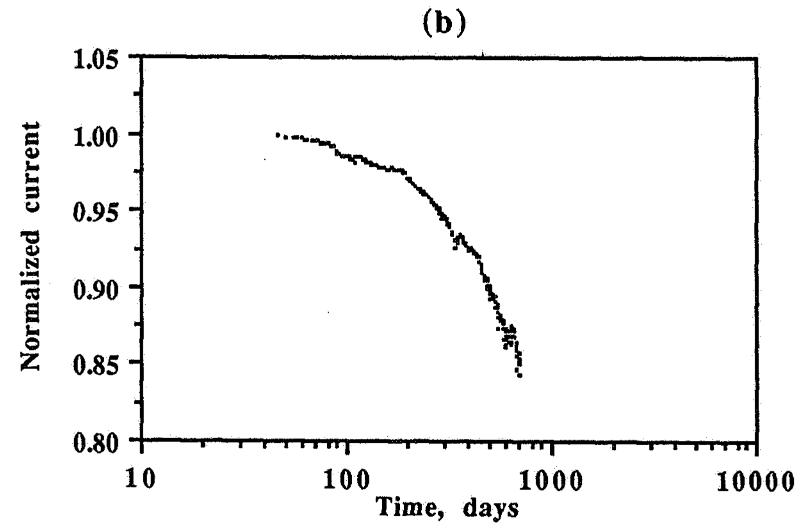
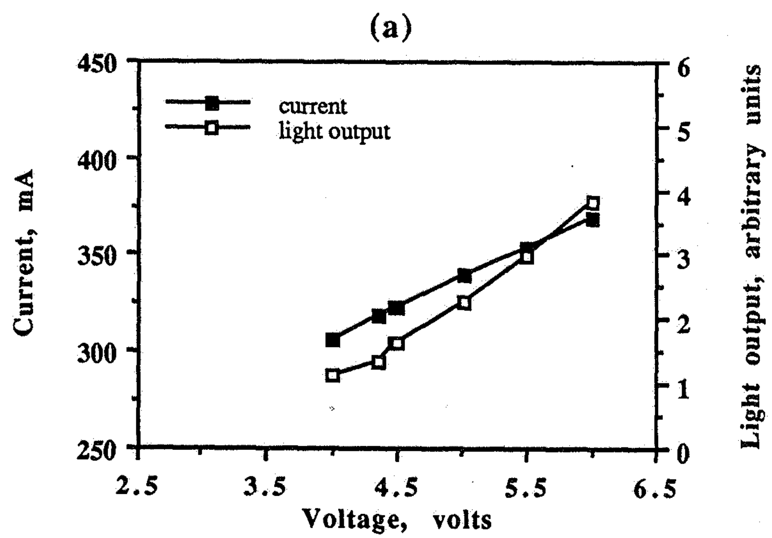


Figure A10. Lamp #2 of Experiment #2. This graph show the light output from the lamp as a function of location along the filament after 663 days of operation. This lamp failed at turn 24 from the left.

SBRC part number: 4-14-11 (93012)
Filament material: GE-218W
Filament diameter: 38.0 µm
Filament length: 3.855 mm
Number of turns: 59
Post contact technique: welded
Operating voltage: 4.477 volts +0.006,-0.037
Burn-in time: 19 days





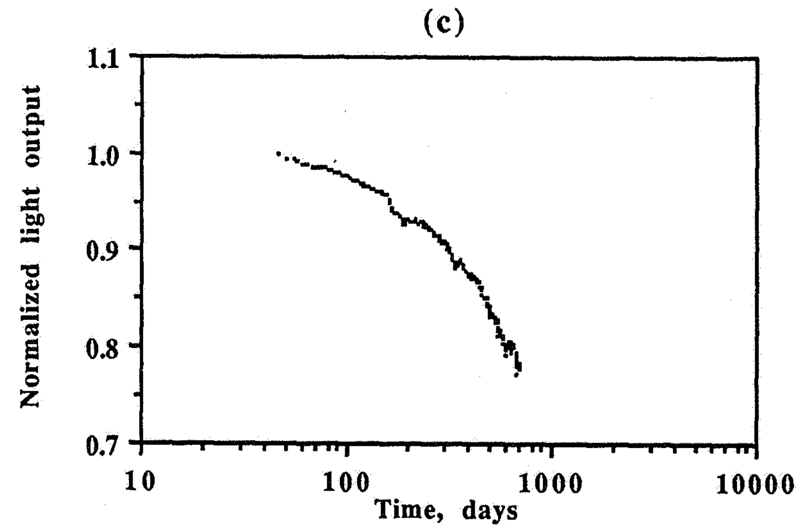


Figure A11. Lamp #3 of Experiment #2. This lamp burned-out after 710 days of operation. This lamp would have passed the burn in test (0.58% decrease in current). This lamp came from the flight lot for GOES-5 and GOES-6. (a) Pre-life test characterization of the lamp. Lamp light output and current vs. voltage. (b) Lamp current vs. days of operation. (c) Lamp light output vs. days of operation.

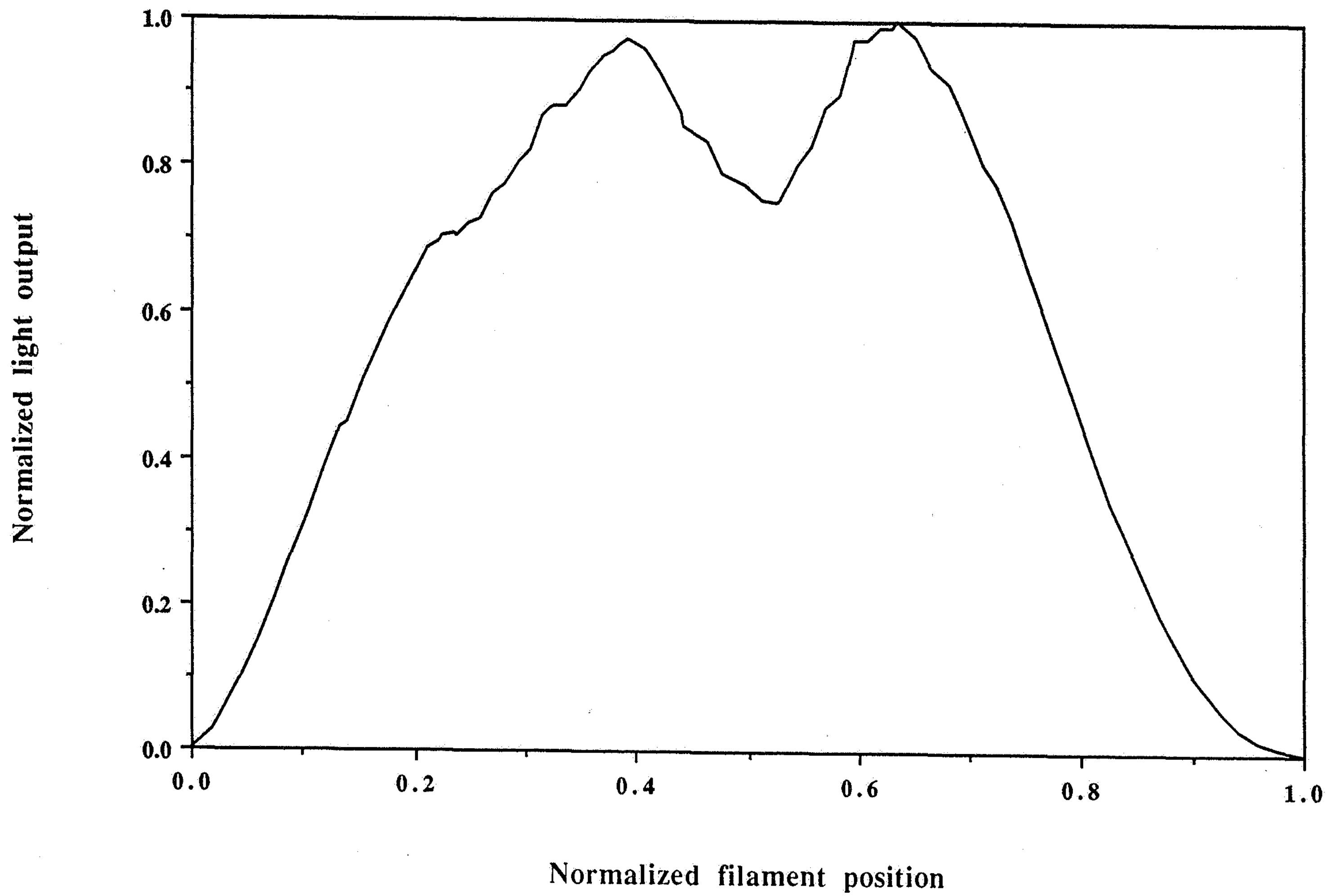


Figure A12. Lamp #3 of Experiment #2. This graph show the light output from the lamp as a function of location along the filament after 661 days of operation. This lamp failed at turn 23 from the left.

SBRC part number: 1-14-12 (93006)
Filament material: GE-218W
Filament diameter: 38.1 µm
Filament length: 3.949 mm
Number of turns: 59
Post contact technique: welded
Operating voltage: 4.477 volts +0.007,-0.002
Burn-in time: 19 days

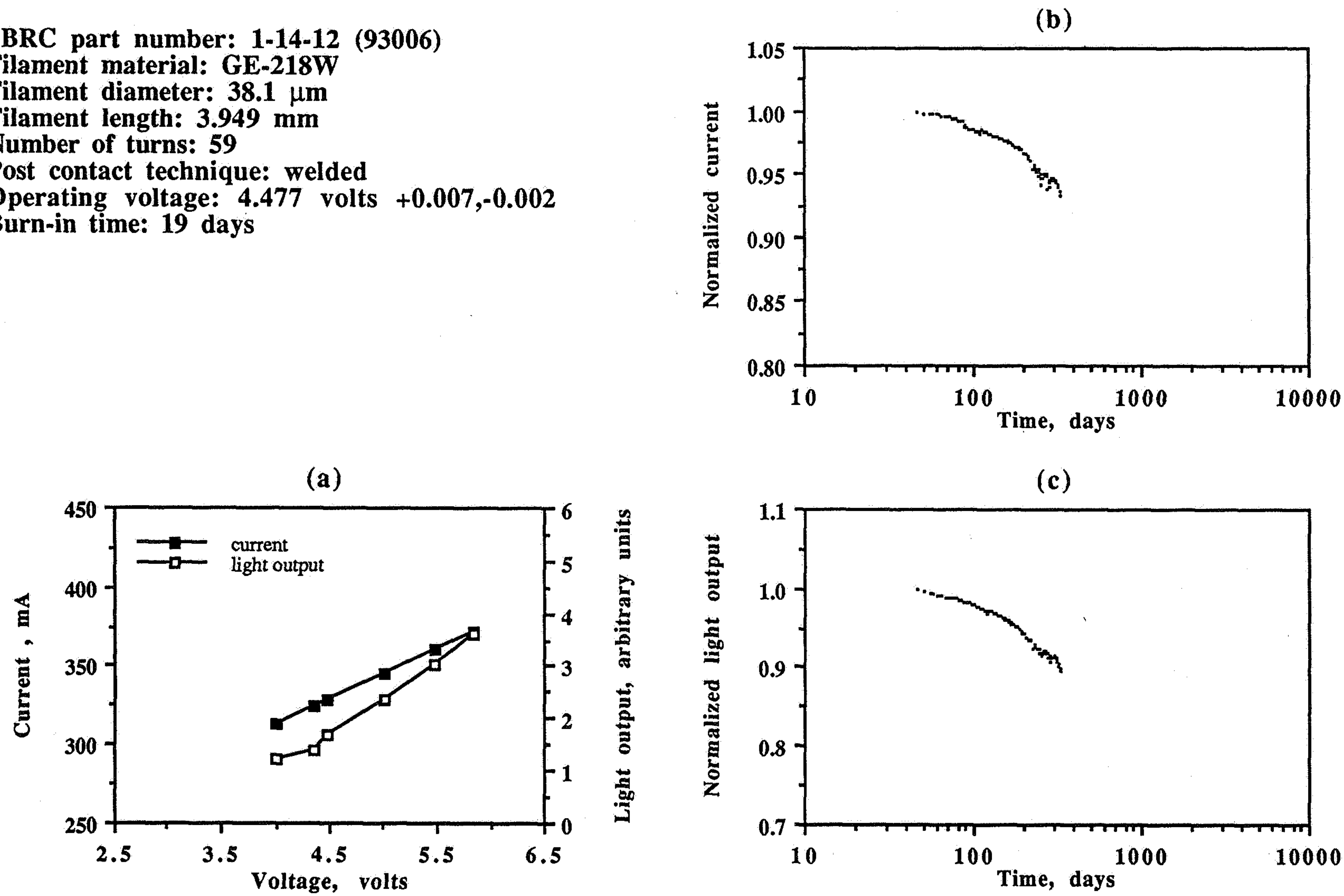
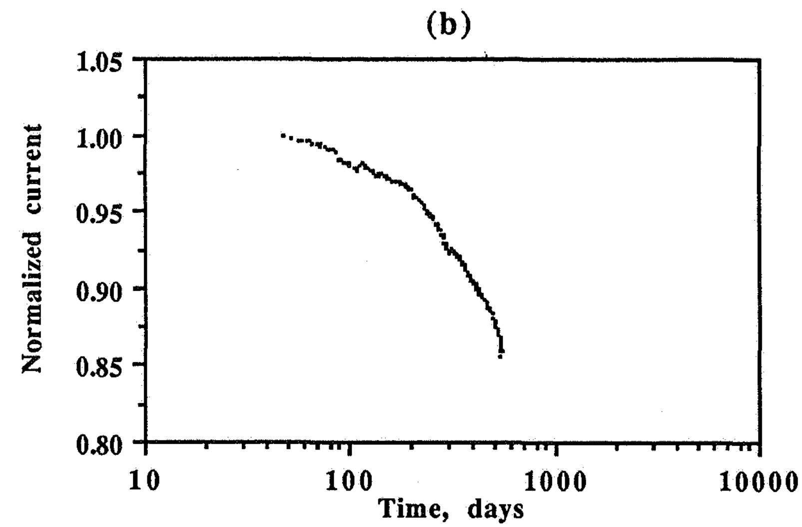
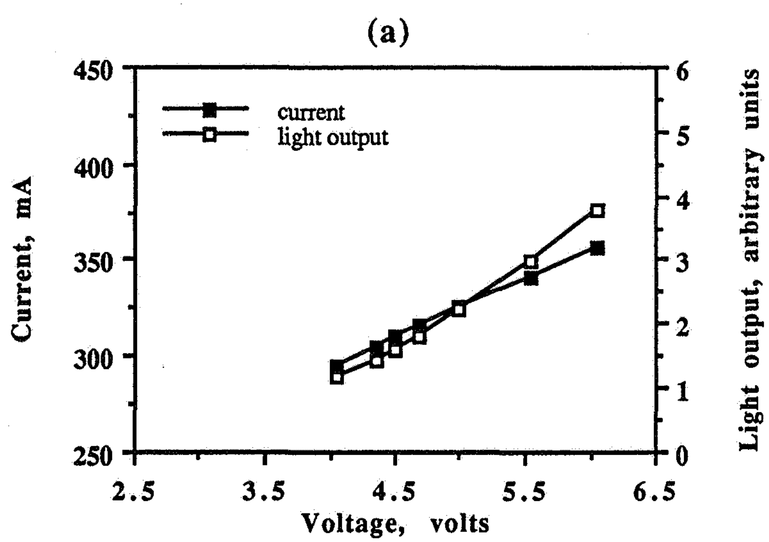


Figure A13. Lamp #4 of Experiment #2. This lamp burned-out after 328 days of operation. This lamp would have passed the burn in test (0.51% decrease in current). This lamp came from the flight lot for GOES-5 and GOES-6. (a) Pre-life test characterization of the lamp. Lamp light output and current vs. voltage. (b) Lamp current vs. days of operation. (c) Lamp light output vs. days of operation.

SBRC part number: 11-14-9 (93054)
Filament material: GE-218W
Filament diameter: 38.1 μm
Filament length: 3.803 mm
Number of turns: 61
Post contact technique: welded
Operating voltage: 4.669 volts +0.005,-0.023
Burn-in time: 21 days





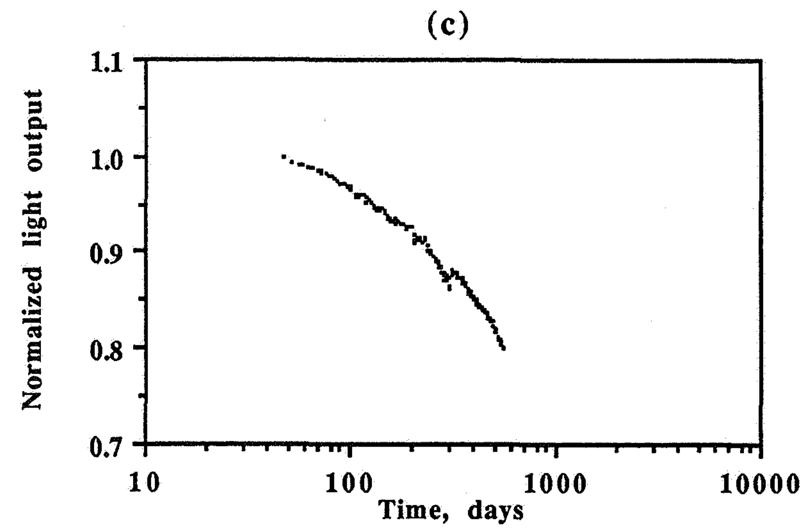
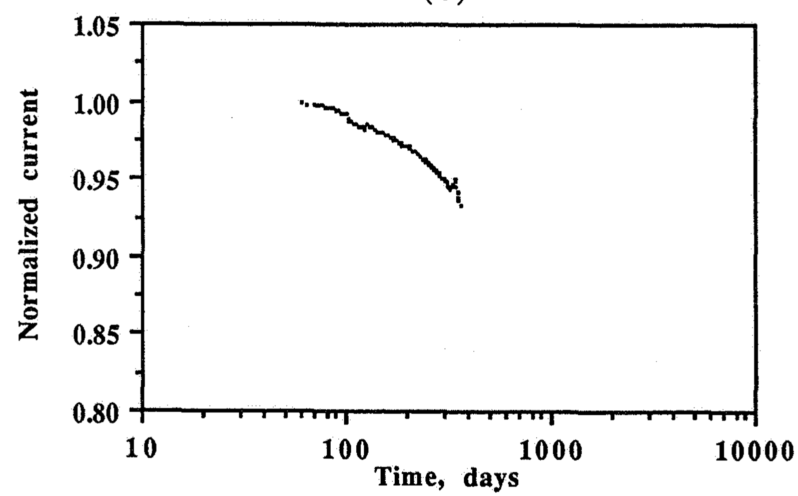


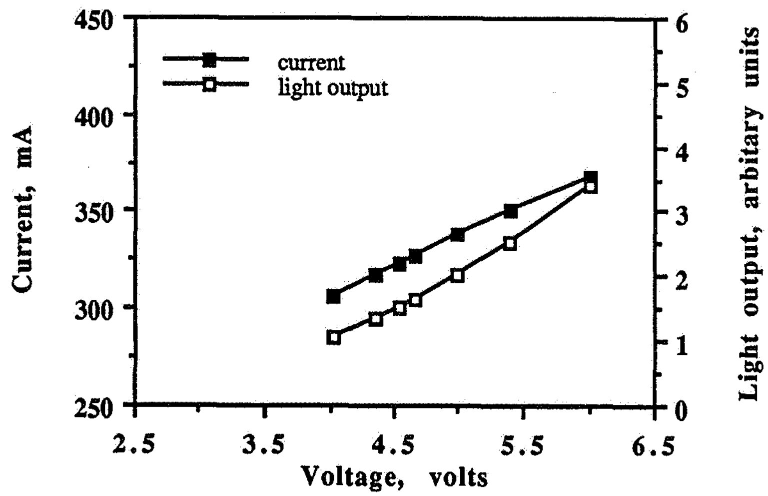
Figure A14. Lamp #5 of Experiment #2. This lamp burned-out after 545 days of operation. This lamp would have passed the burn in test (0.35% decrease in current). This lamp came from the flight lot for GOES-5 and GOES-6. (a) Pre-life test characterization of the lamp. Lamp light output and current vs. voltage. (b) Lamp current vs. days of operation. (c) Lamp light output vs. days of operation.

SBRC part number: 3-14-9 (93063)
Filament material: GE-218W
Filament diameter: 38.5 µm
Filament length: 3.710 mm
Number of turns: 61
Post contact technique: welded
Operating voltage: 4.666 volts +0.008,-0.069
Burn-in time: 33 days

(b)



(a)



(c)

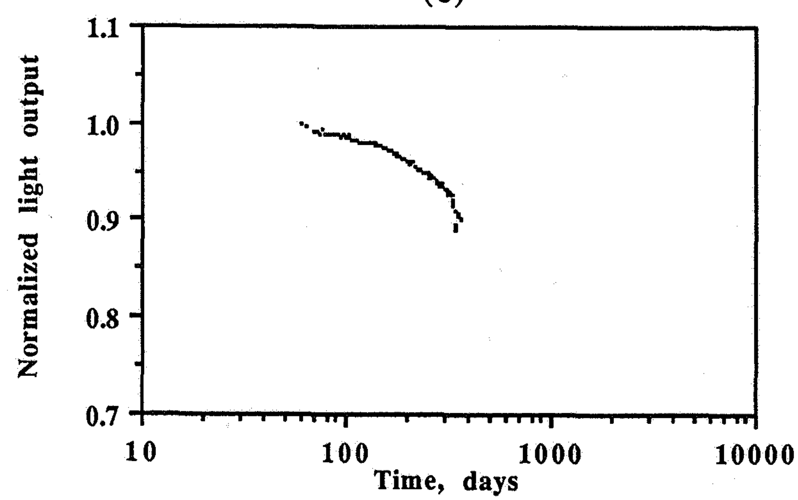


Figure A15. Lamp #6 of Experiment #2. This lamp burned-out after 362 days of operation. This lamp would have passed the burn in test (0.64% decrease in current). This lamp came from the flight lot for GOES-5 and GOES-6. (a) Pre-life test characterization of the lamp. Lamp light output and current vs. voltage. (b) Lamp current vs. days of operation. (c) Lamp light output vs. days of operation.

SBRC part number: 4-14-10 (93011)
Filament material: GE-218W
Filament diameter: 36.3 μm
Filament length: 3.843 mm
Number of turns: 60
Post contact technique: welded
Operating voltage: 4.674 volts +0.007,-0.025
Burn-in time: 19 days

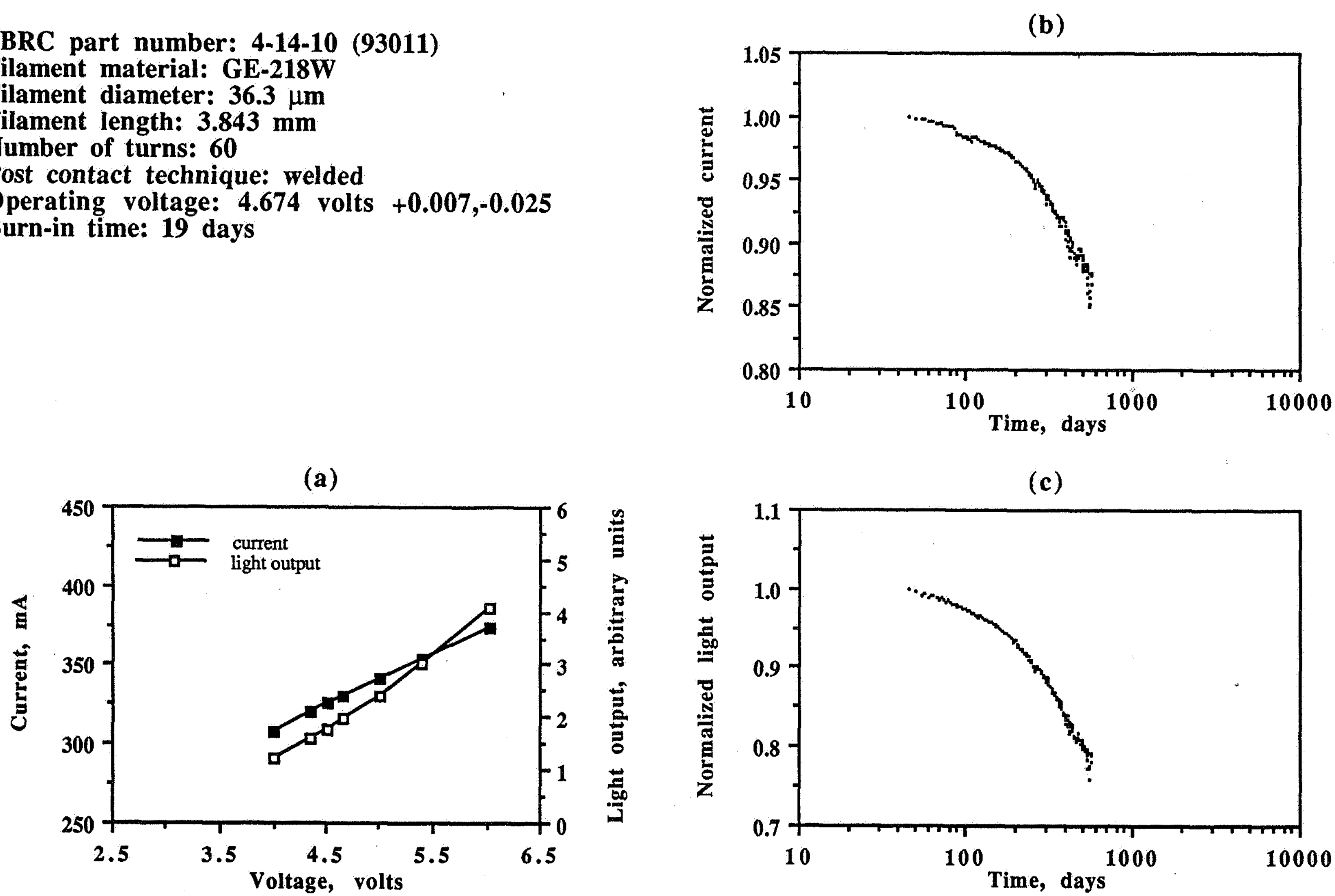


Figure A16. Lamp #7 of Experiment #2. This lamp burned-out after 578 days of operation. This lamp would have passed the burn in test (0.52% decrease in current). This lamp came from the flight lot for GOES-5 and GOES-6. (a) Pre-life test characterization of the lamp. Lamp light output and current vs. voltage. (b) Lamp current vs. days of operation. (c) Lamp light output vs. days of operation.

SBRC part number: 11-14-8 (93059)
Filament material: GE-218W
Filament diameter: 38.3 μm
Filament length: 3.768 mm
Number of turns: 58
Post contact technique: welded
Operating voltage: 4.863 volts +0.004,-0.001
Burn-in time: 21 days

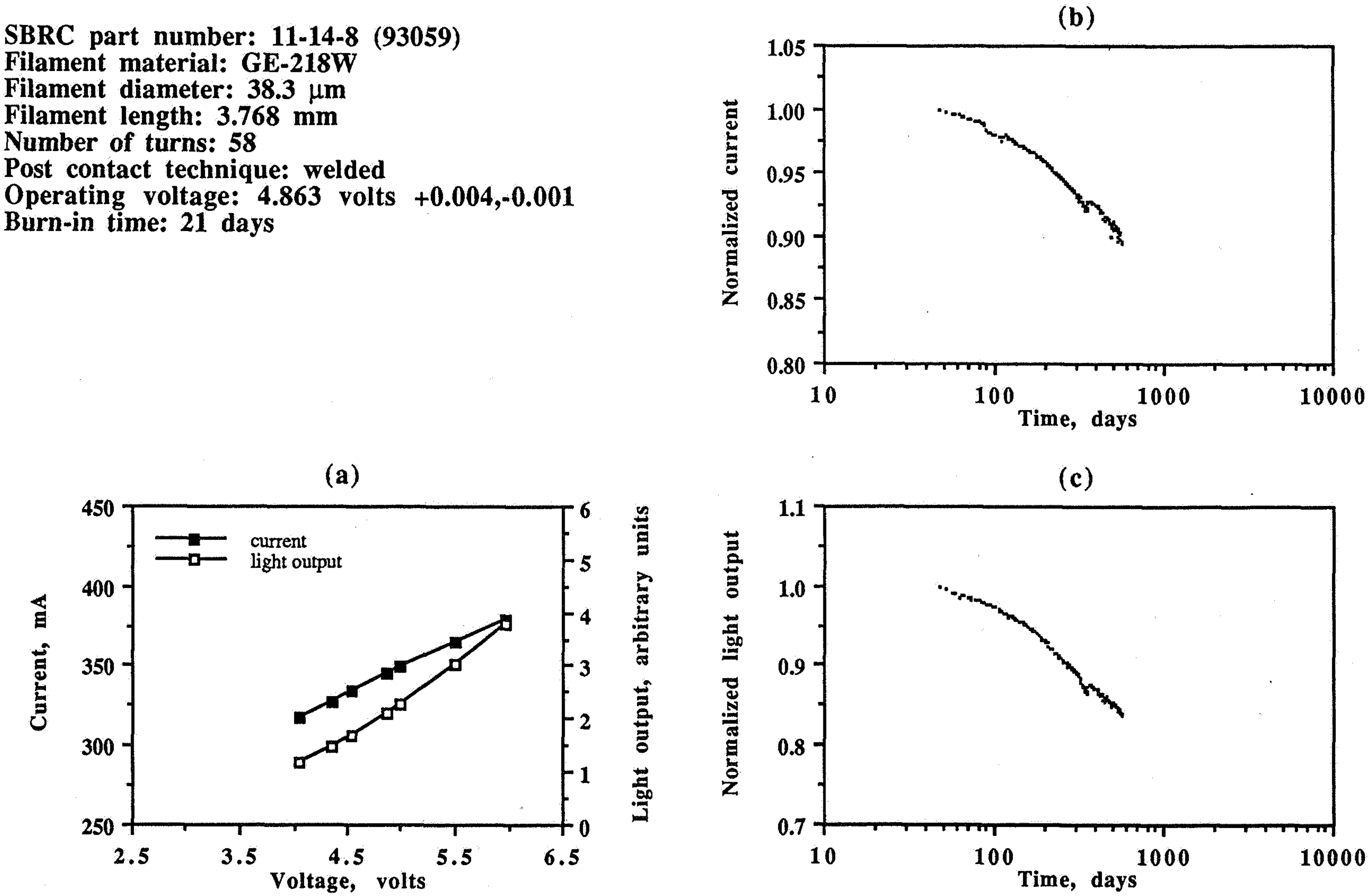
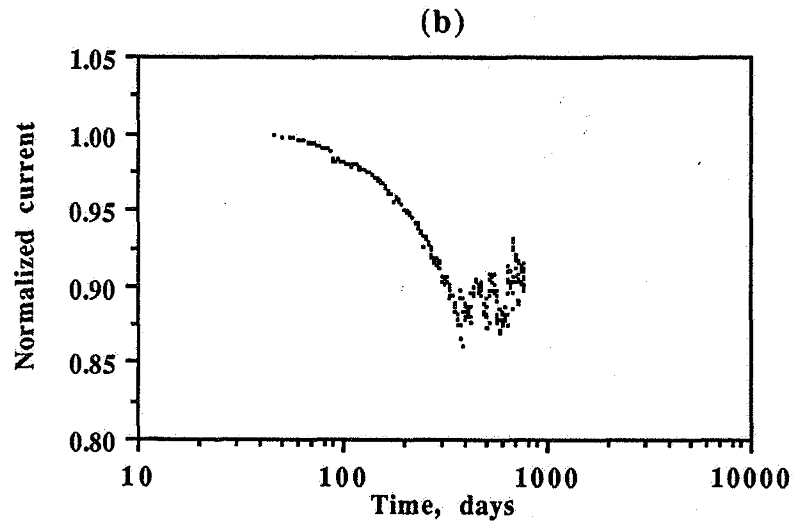
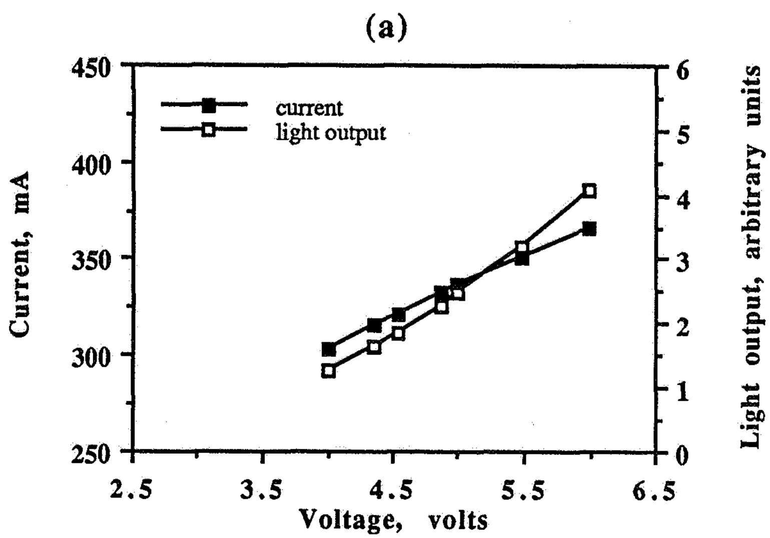


Figure A17. Lamp #8 of Experiment #2. This lamp burned-out after 566 days of operation. This lamp would have passed the burn in test (0.65% decrease in current). This lamp came from the flight lot for GOES-5 and GOES-6. (a) Pre-life test characterization of the lamp. Lamp light output and current vs. voltage. (b) Lamp current vs. days of operation. (c) Lamp light output vs. days of operation.

SBRC part number: 1-14-10 (93084)
Filament material: GE-218W
Filament diameter: 38.4 μm
Filament length: 3.593 mm
Number of turns: 60
Post contact technique: welded
Operating voltage: 4.856 volts +0.008,-0.027
Burn-in time: 19 days





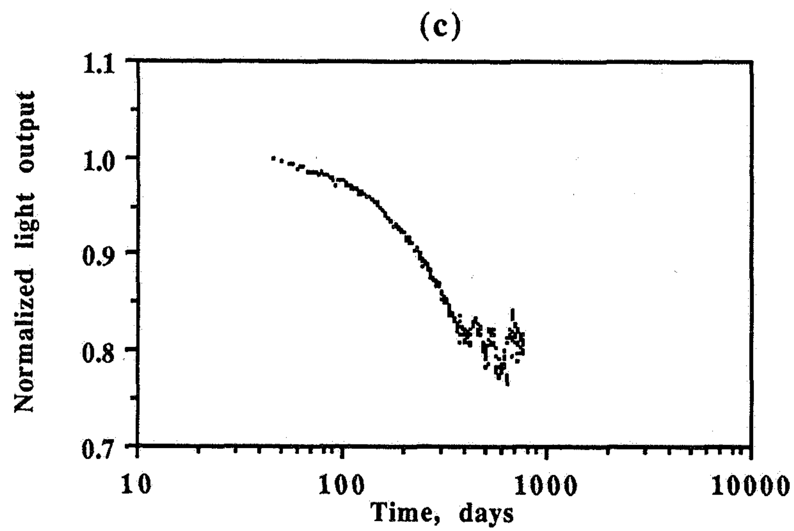


Figure A18. Lamp #9 of Experiment #2. This lamp burned-out after 774 days of operation. This lamp would have passed the burn in test (0.53% decrease in current). This lamp came from the flight lot for GOES-5 and GOES-6. (a) Pre-life test characterization of the lamp. Lamp light output and current vs. voltage. (b) Lamp current vs. days of operation. (c) Lamp light output vs. days of operation.

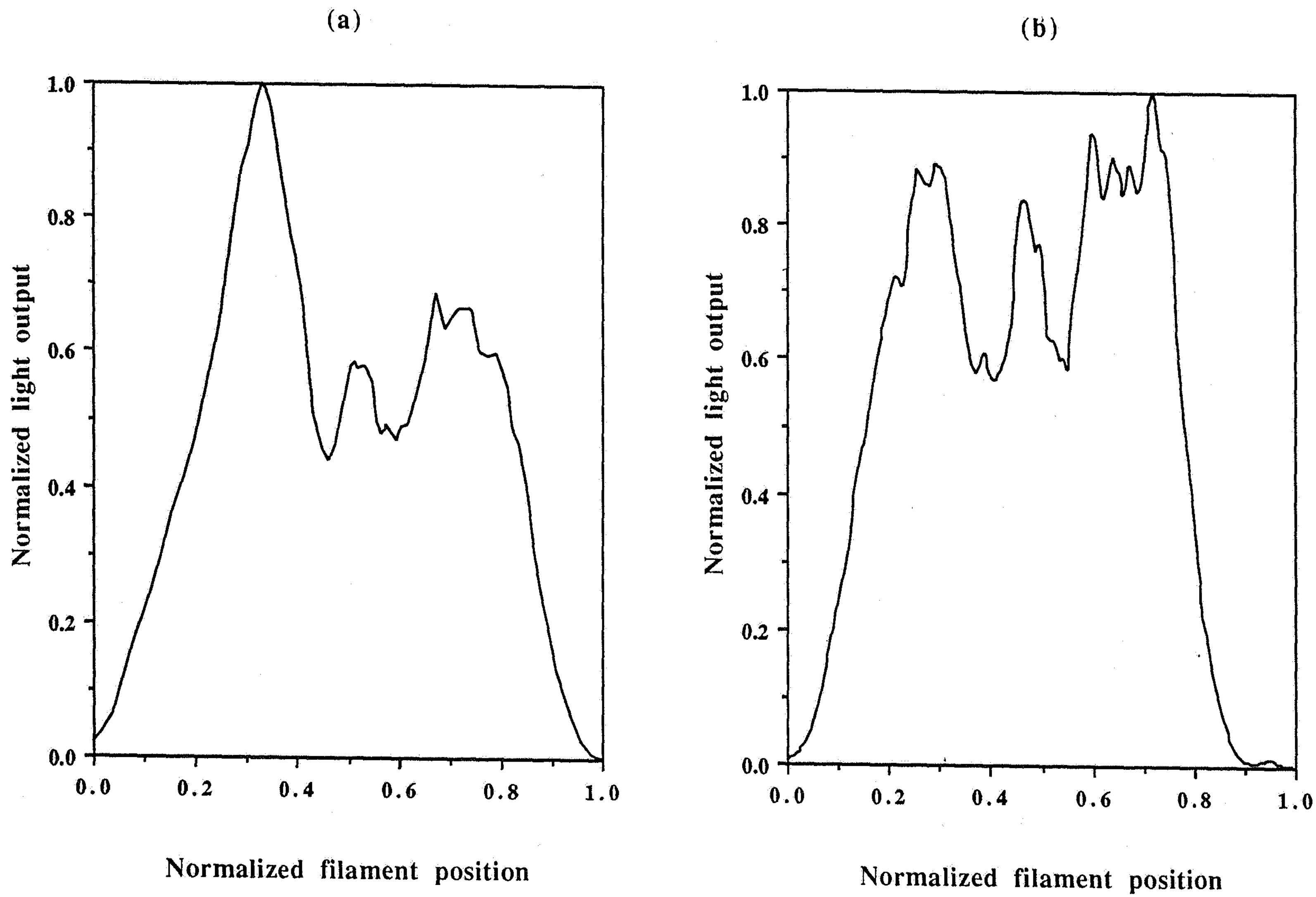
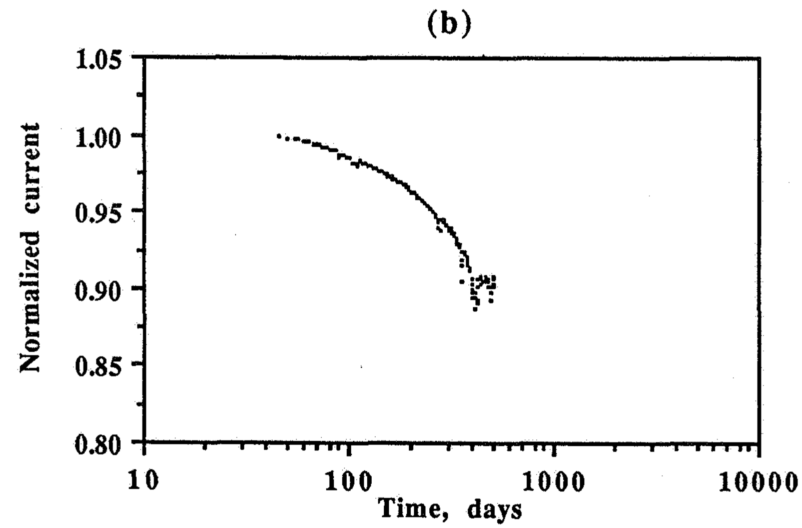
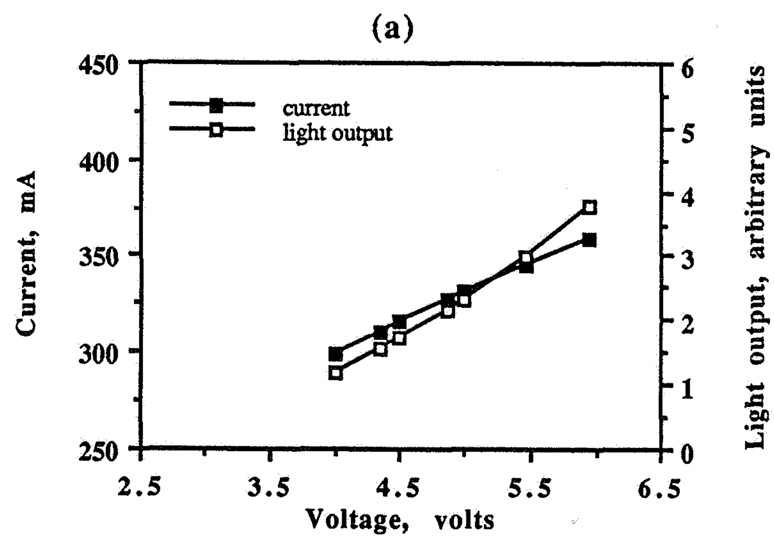


Figure A19. Lamp #9 of Experiment #2. These graphs show the light output from the lamp as a function of location along the filament. This lamp failed at turn 38 from the left. Distortion of the filament occurred during the life test. (a) 661 days of operation. (b) 739 days of operation.

SBRC part number: 10-14-12 (93024)
Filament material: GE-218W
Filament diameter: not measured
Filament length: not measured
Number of turns: not measured
Post contact technique: welded
Operating voltage: 4.867 volts +0.008,-0.025
Burn-in time: 19 days





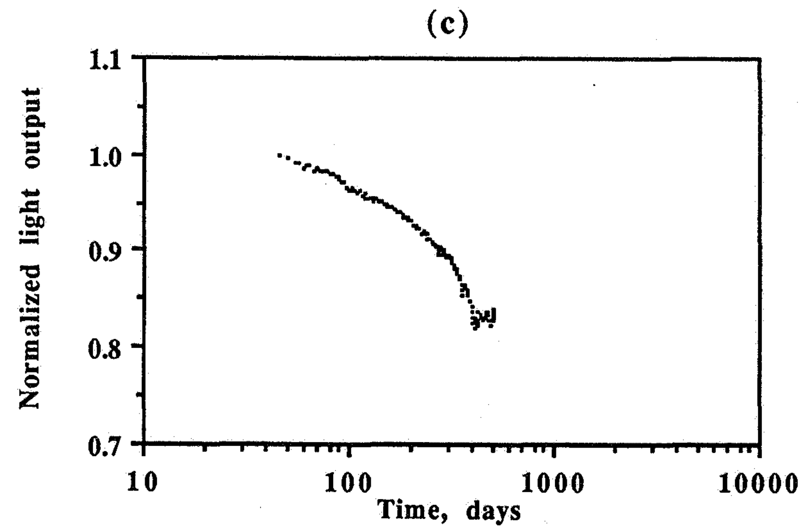


Figure A20. Lamp #10 of Experiment #2. This lamp burned-out after 508 days of operation. This lamp would have passed the burn in test (0.54% decrease in current). This lamp came from the flight lot for GOES-5 and GOES-6. (a) Pre-life test characterization of the lamp. Lamp light output and current vs. voltage. (b) Lamp current vs. days of operation. (c) Lamp light output vs. days of operation.

SBRC part number: 7-14-6 (93060)
Filament material: GE-218W
Filament diameter: 37.5 μm
Filament length: 3.987 mm
Number of turns: 62
Post contact technique: welded
Operating voltage: 4.993 volts +0.010,-0.047
Burn-in time: 20 days

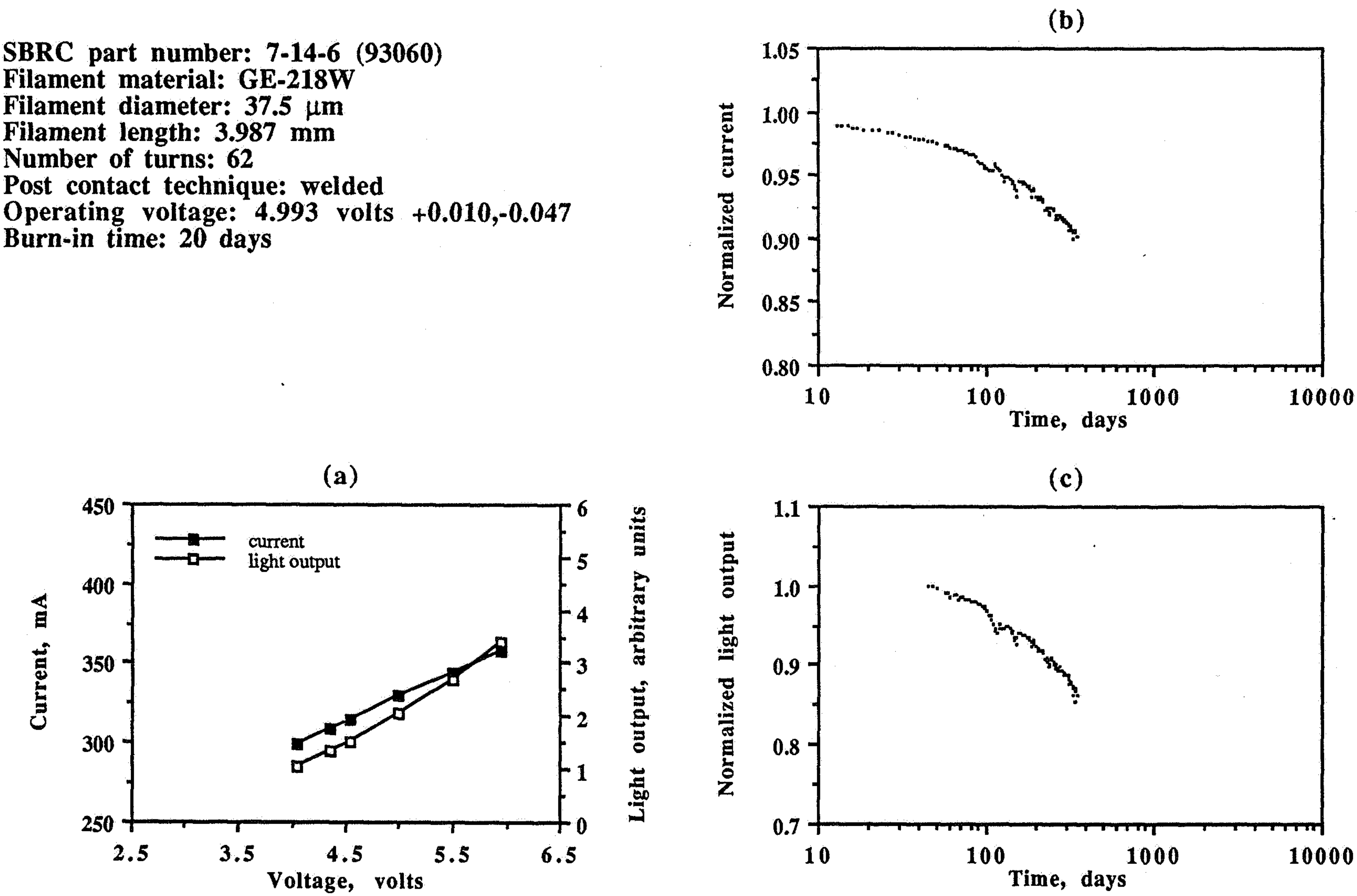


Figure A21. Lamp #11 of Experiment #2. This lamp burned-out after 351 days of operation. This lamp would have passed the burn in test (0.77% decrease in current). This lamp came from the flight lot for GOES-5 and GOES-6. (a) Pre-life test characterization of the lamp. Lamp light output and current vs. voltage. (b) Lamp current vs. days of operation. (c) Lamp light output vs. days of operation.

SBRC part number: 5-14-6 (93053)
Filament material: GE-218W
Filament diamter: not measured
Filament length: not measured
Number of turns: not measured
Post contact technique: welded
Operating voltage: 5.000 volts +0.003,-0.008
Burn-in time: 20 days

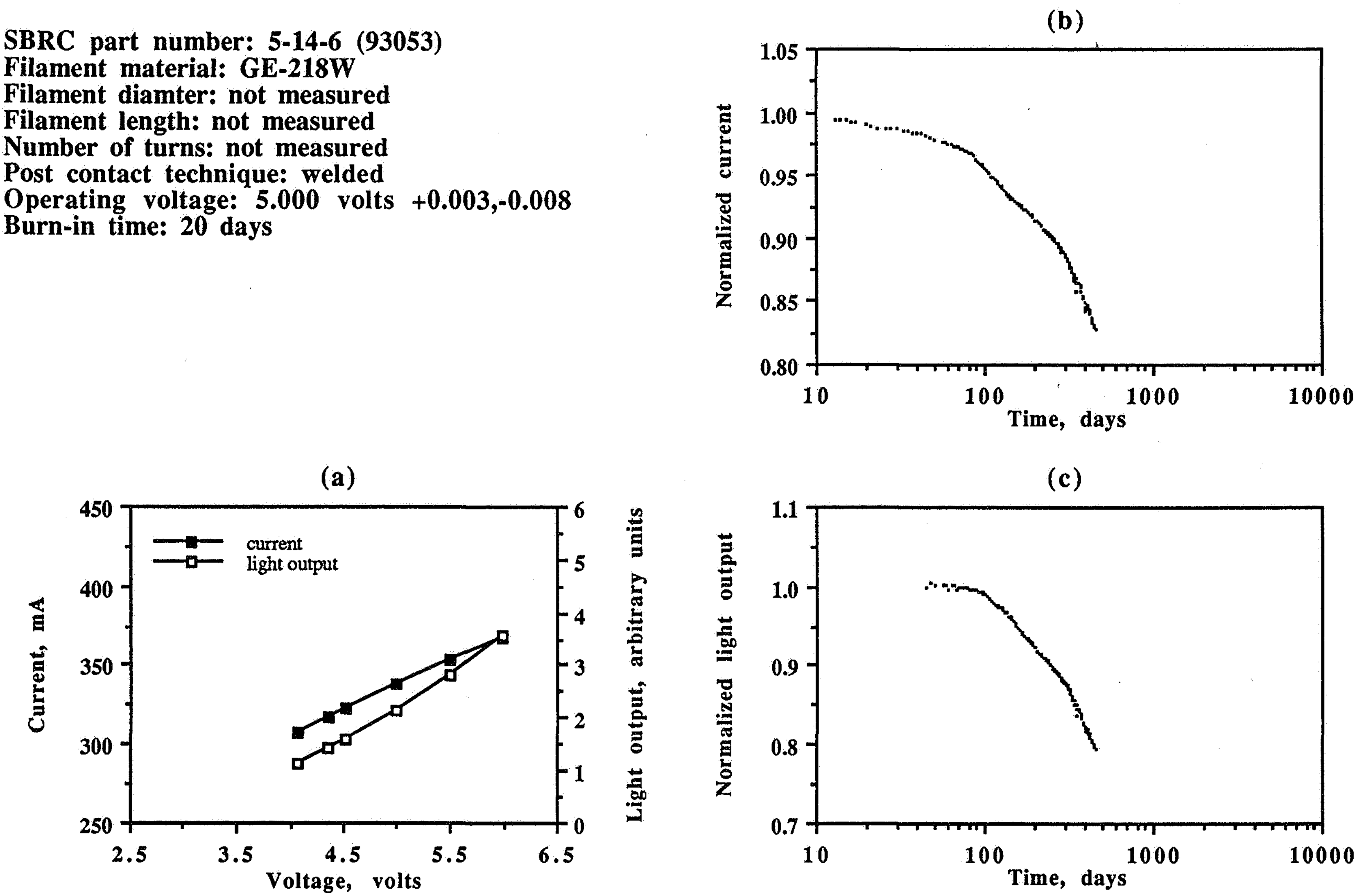


Figure A22. Lamp #12 of Experiment #2. This lamp burned-out after 455 days of operation. This lamp would have failed the burn in test (1.09% decrease in current). This lamp came from the flight lot for GOES-5 and GOES-6. (a) Pre-life test characterization of the lamp. Lamp light output and current vs. voltage. (b) Lamp current vs. days of operation. (c) Lamp light output vs. days of operation.

SBRC part number: none
Filament material: GE-218W
Filament diameter: 39.2 μm
Filament length: 3.552 mm
Number of turns: 57
Post contact technique: welded
Operating voltage: 3.535 volts +0.005,-0.066
Burn-in time: none

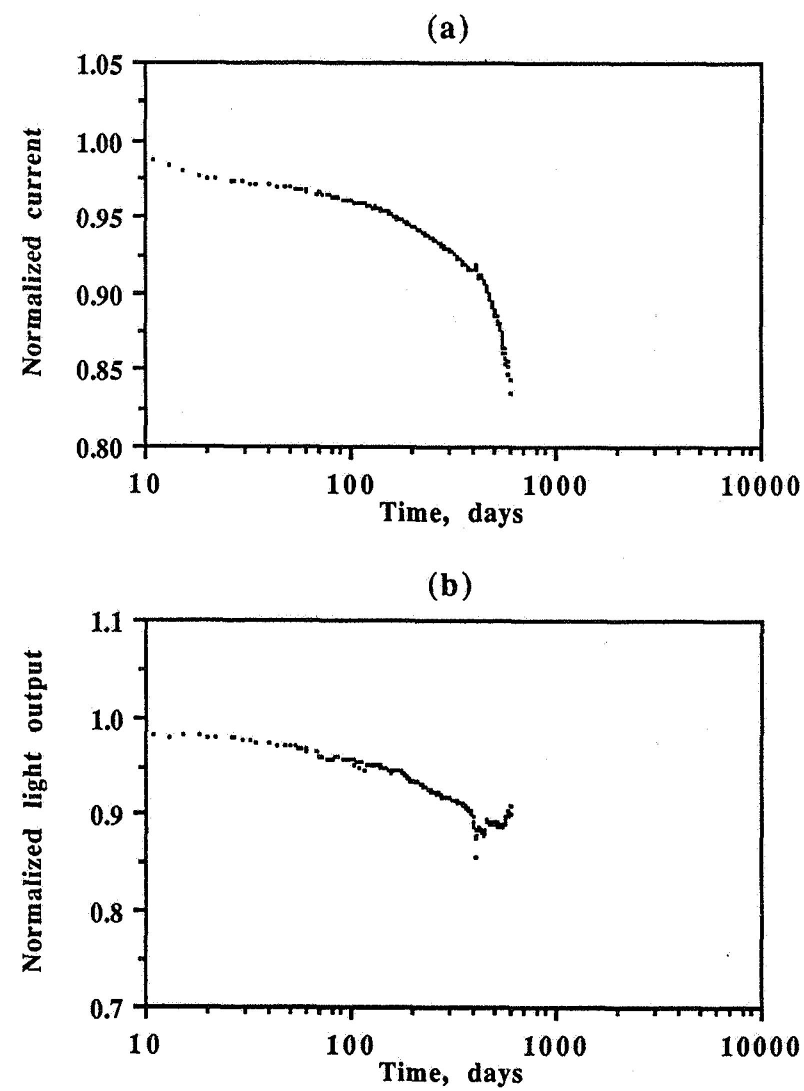


Figure A23. Lamp #1 of Experiment #3. This lamp burned-out after 598 days of operation. No pre-life test characterization was performed on this lamp. (a) Lamp current vs. days of operation. (b) Lamp light output vs. days of operation.

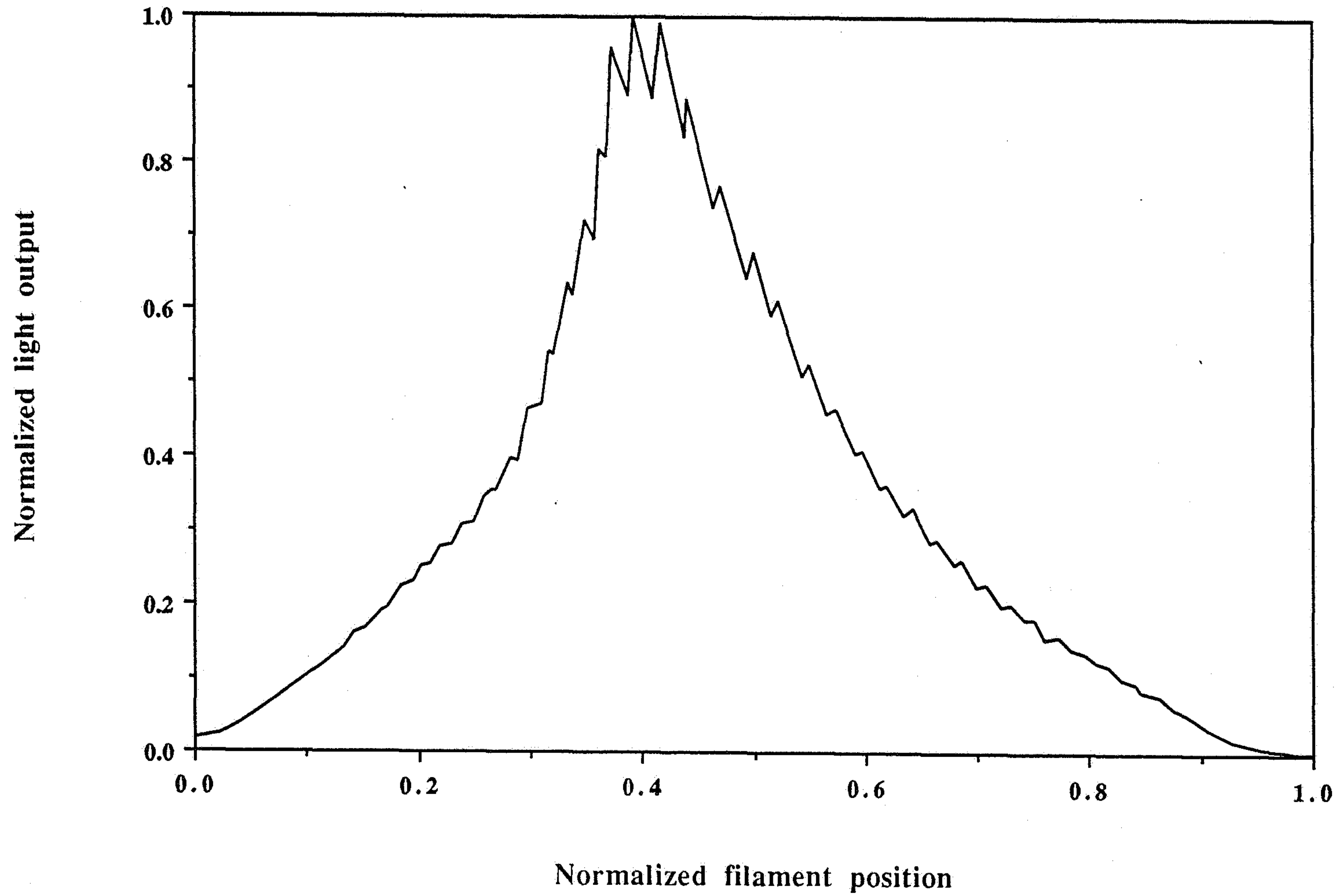


Figure A24. Lamp #1 of Experiment #3. This graph shows the light output from the lamp as a function of location along the filament after 530 days of operation. This lamp failed at turn 27 from the left. This lamp had a visible "hot-spot" during the entire life test.

SBRC part number: 8-14-17
Filament material: GE-218W
Filament diameter: 36.9 μm
Filament length: 3.878 mm
Number of turns: 62
Post contact technique: welded
Operating voltage: 3.529 volts +0.010,-0.026
Burn-in time: none

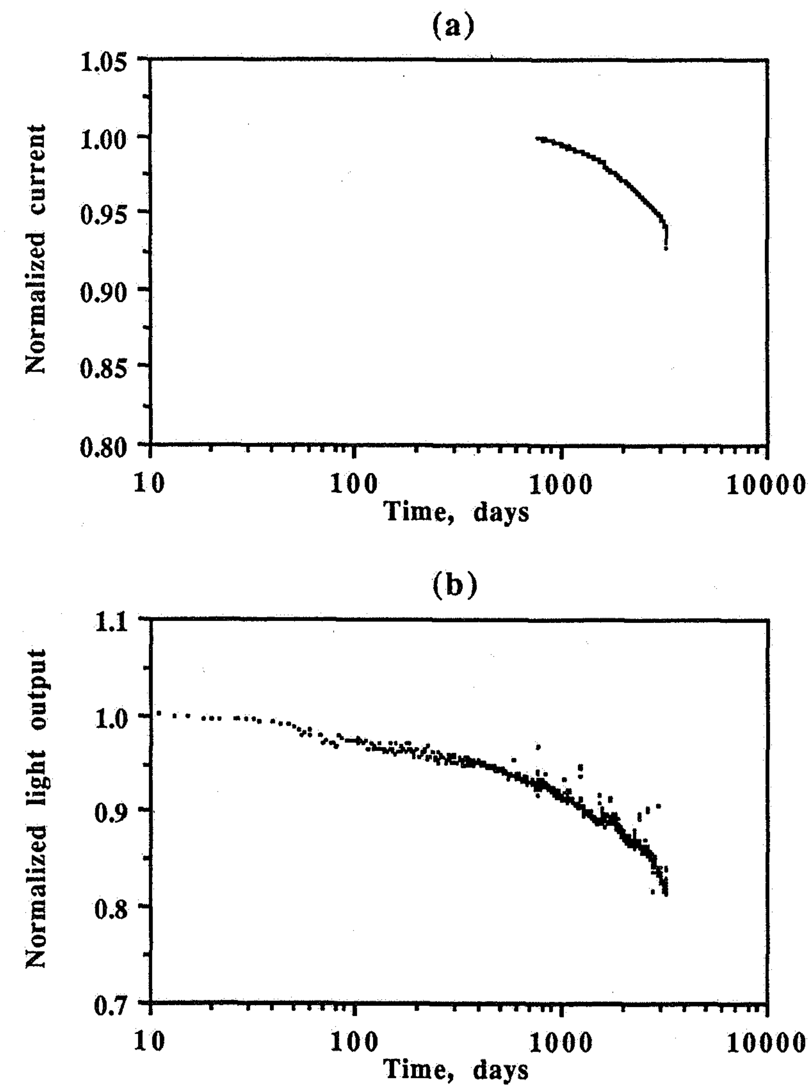


Figure A25. Lamp #2 of Experiment #3. This lamp burned-out after 3223 days of operation. No pre-life test characterization was performed on this lamp. (a) Lamp current vs. days of operation. (b) Lamp light output vs. days of operation.

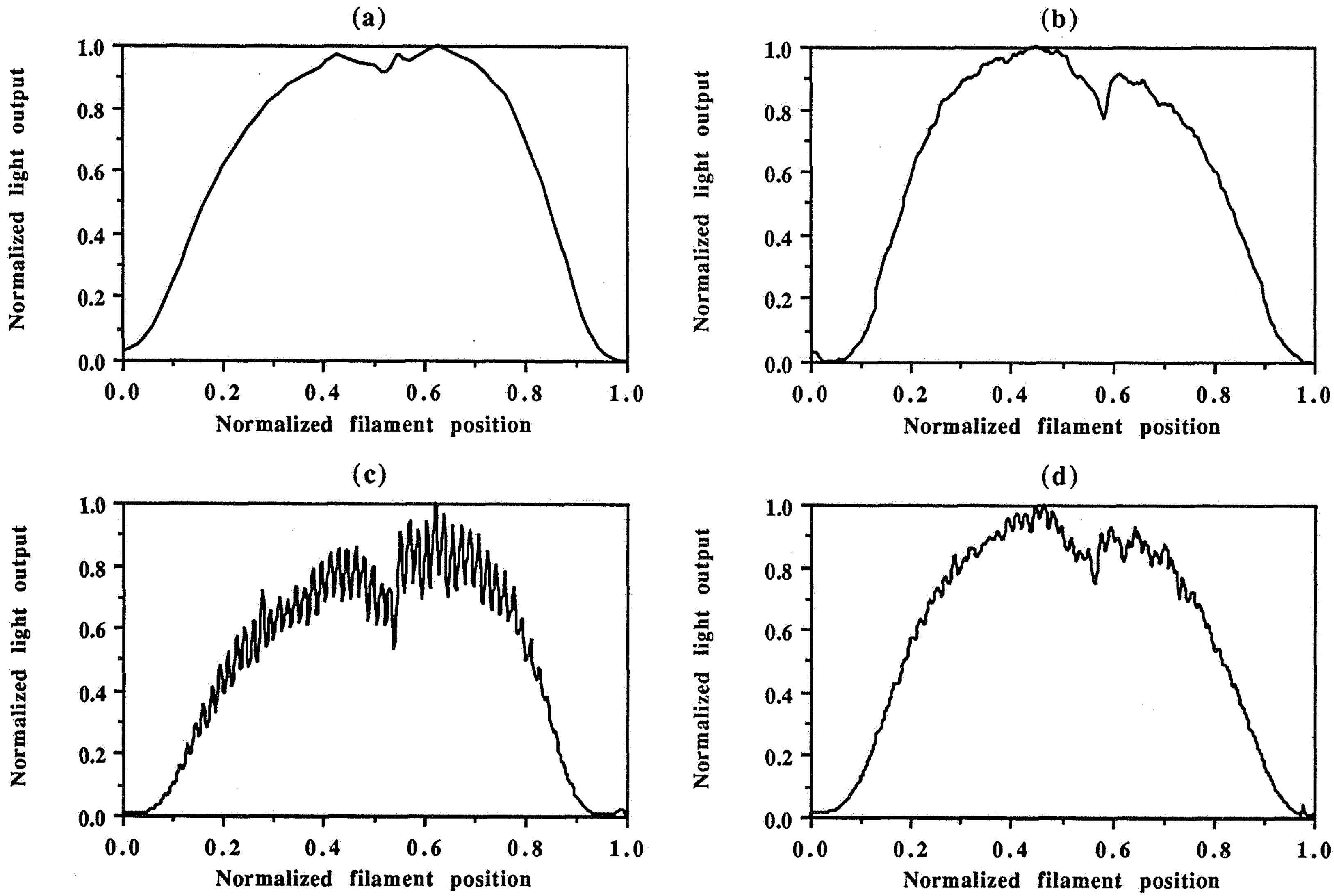


Figure A26. Lamp #2 of Experiment #3. These graphs show the light output from the lamp as a function of location along the filament. This lamp failed at turn 24 from the left. (a) 528 days of operation. (b) 606 days of operation. (c) 1291 days of operation. (d) 1976 days of operation.

SBRC part number: none
Filament material: GE-218W
Filament diameter: 39.5 μm
Filament length: 3.585 mm
Number of turns: 60
Post contact technique: welded
Operating voltage: 4.483 volts +0.008,-0.015
Burn-in time: none

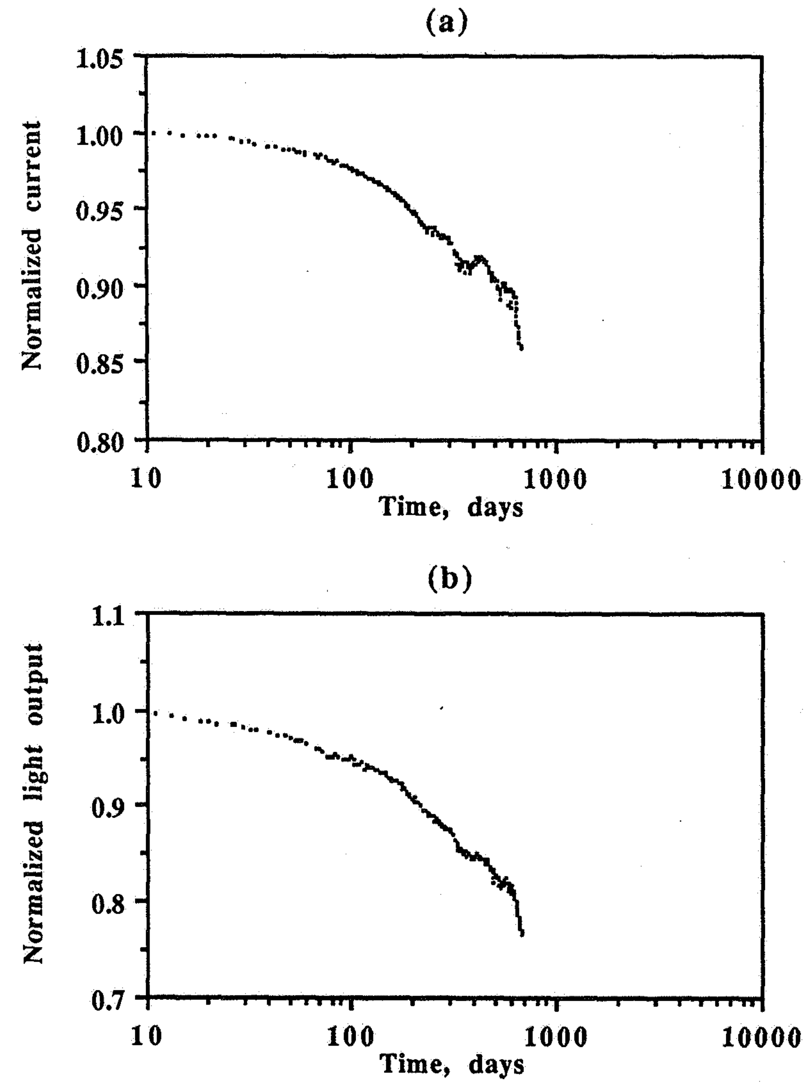


Figure A27. Lamp #7 of Experiment #3. This lamp burned-out after 676 days of operation. A leak in the epoxy base caused this lamp to fail. No pre-life test characterization was performed on this lamp. (a) Lamp current vs. days of operation. (b) Lamp light output vs. days of operation.

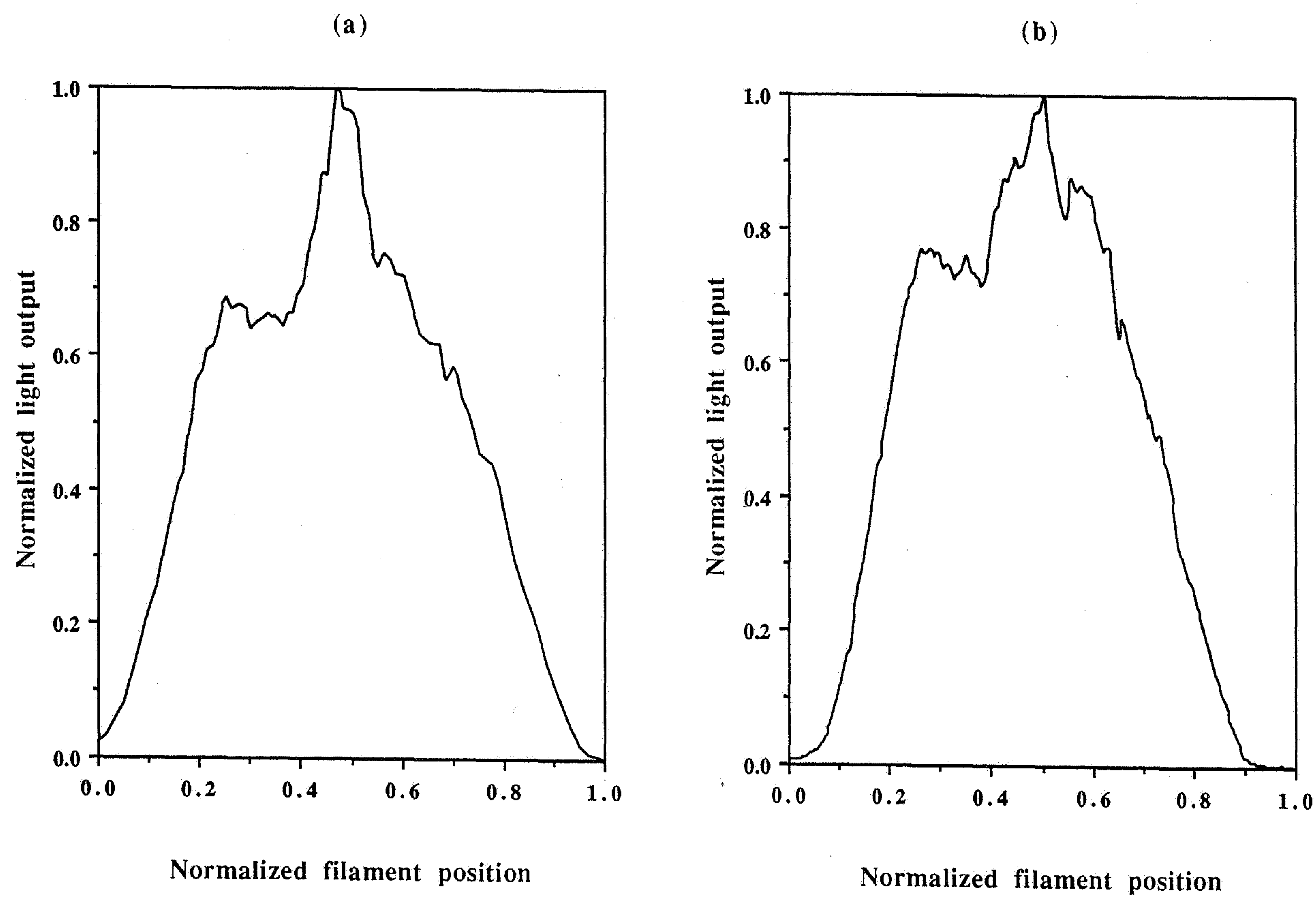


Figure A28. Lamp #7 of Experiment #3. These graphs show the light output from the lamp as a function of location along the filament. This lamp failed at turn 17 from the left. (a) 528 days of operation. (b) 606 days of operation.

SBRC part number: none
Filament material: GE-218W
Filament diameter: 37.4 µm
Filament length: 3.542 mm
Number of turns: 60
Post contact technique: welded
Operating voltage: 4.483 volts +0.001,-0.002
Burn-in time: none

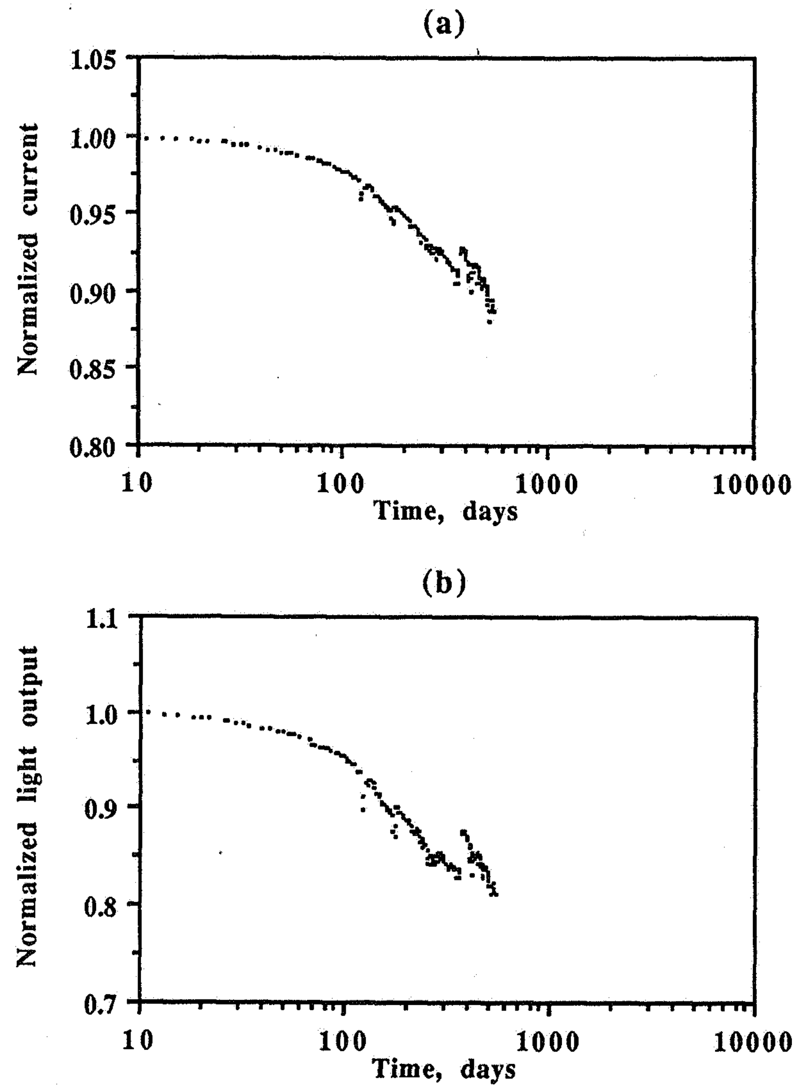


Figure A29. Lamp #8 of Experiment #3. This lamp burned-out after 543 days of operation. No pre-life test characterization was performed on this lamp. (a) Lamp current vs. days of operation. (b) Lamp light output vs. days of operation.

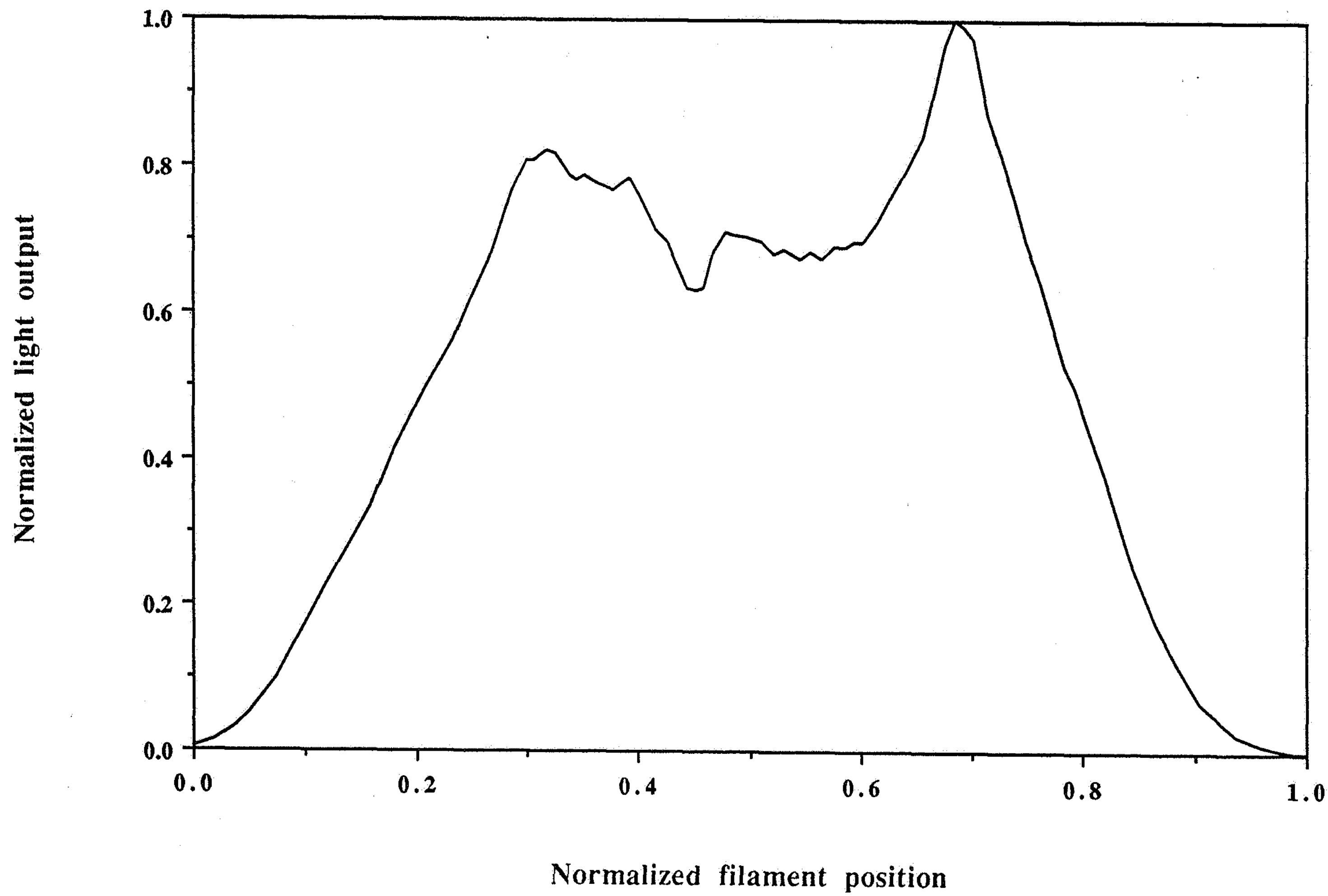


Figure A30. Lamp #8 of Experiment #3. This graph shows the light output from the lamp as a function of location along the filament after 528 days of operation. This lamp failed at turn 40 from the left.

SBRC part number: 54967-2 (Lot F-2)
Filament material: GE 3D-EESM
Filament diameter: not measured
Filament length: not measured
Number of turns: 51
Post contact technique: brazed
Operating voltage: 3.550 volts +0.003,-0.008
Burn-in time: none

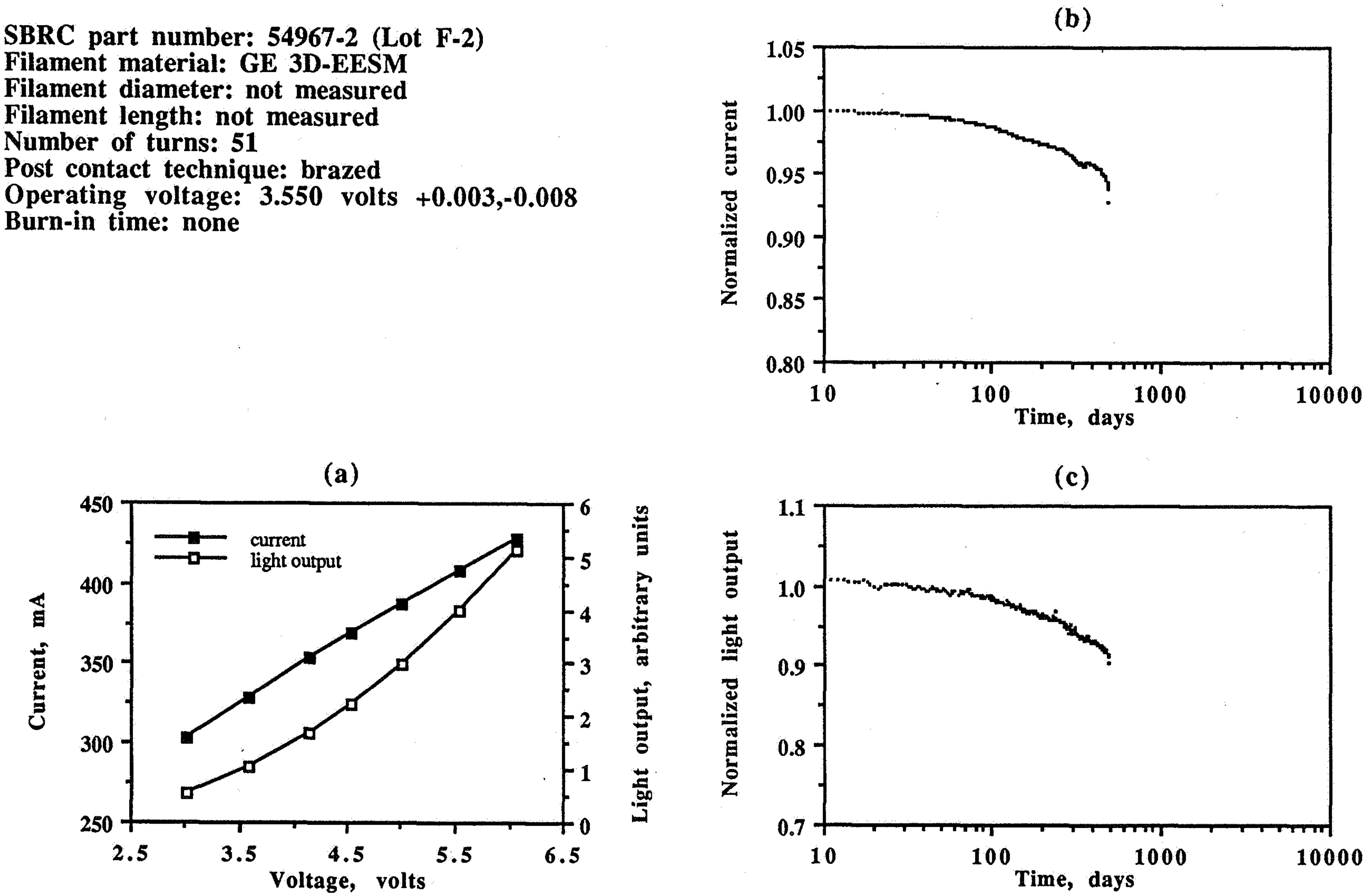


Figure A31. Lamp #1 of Experiment #4. This lamp burned-out after 488 days of operation. (a) Pre-life test characterization of the lamp. Lamp light output and current vs. voltage. (b) Lamp current vs. days of operation. (c) Lamp light output vs. days of operation.

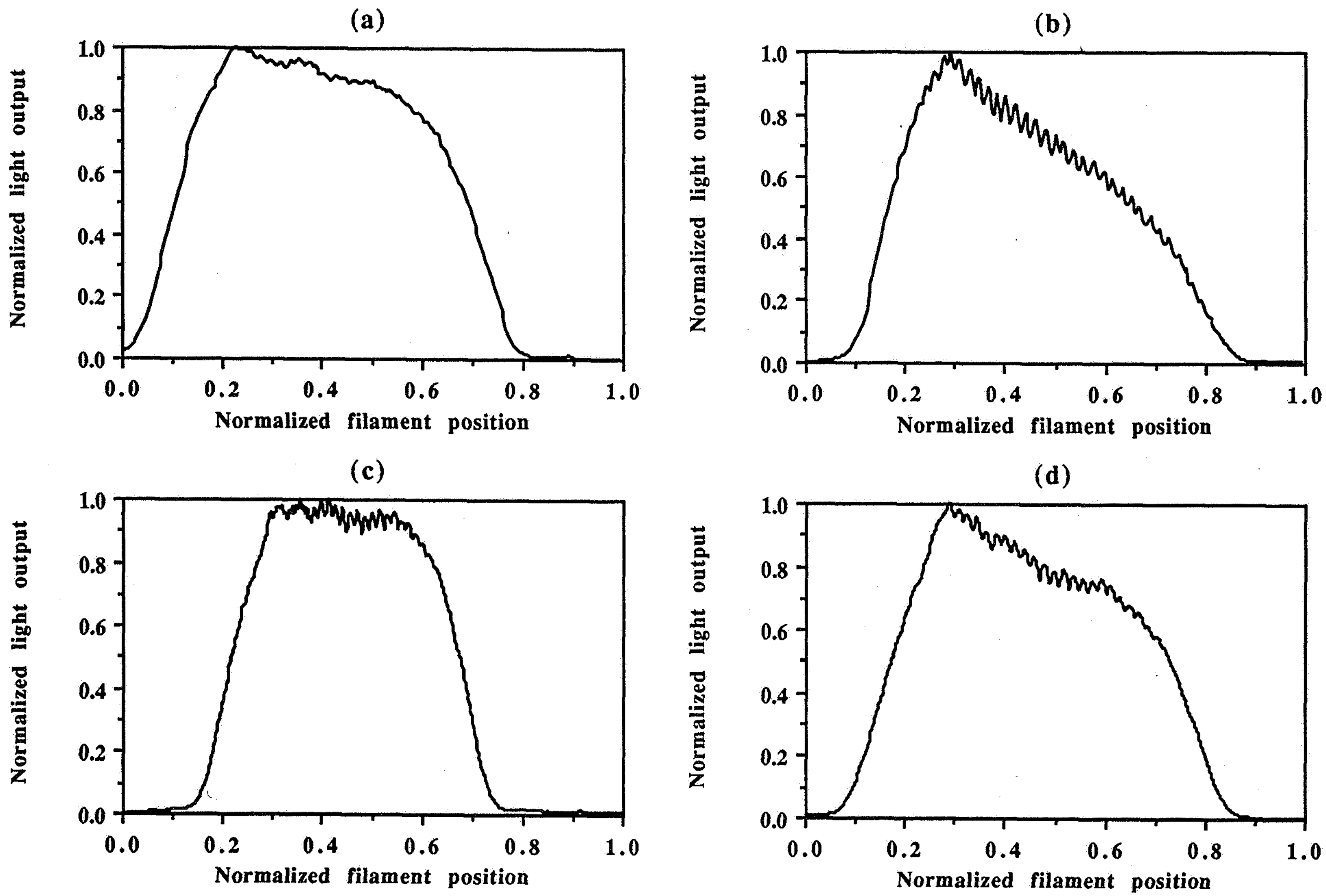


Figure A32. Lamp #1 of Experiment #4. These graphs show the light output from the lamp as a function of location along the filament. (a) 106 days of operation. (b) 211 days of operation. (c) 319 days of operation. (d) 443 days of operation.

SBRC part number: 54967-2 (Lot F-2)
Filament material: GE 3D-EESM
Filament diameter: not measured
Filament length: not measured
Number of turns: not measured
Post contact technique: brazed
Operating voltage: 3.553 volts +0.027,-0.023
Burn-in time: none

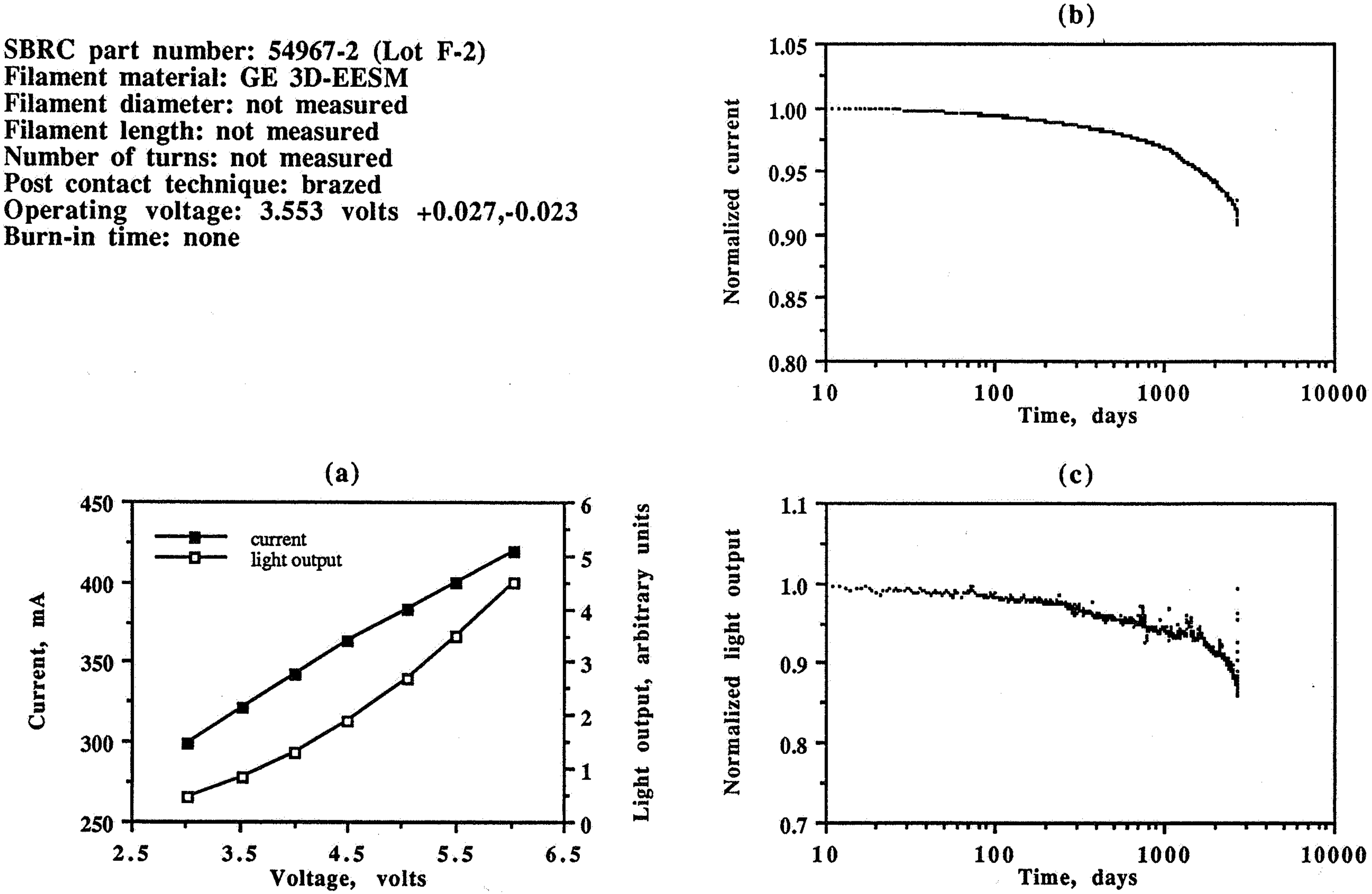


Figure A33. Lamp #2 of Experiment #4. This lamp was still operating after 2700 days. (a) Pre-life test characterization of the lamp. Lamp light output and current vs. voltage. (b) Lamp current vs. days of operation. (c) Lamp light output vs. days of operation.

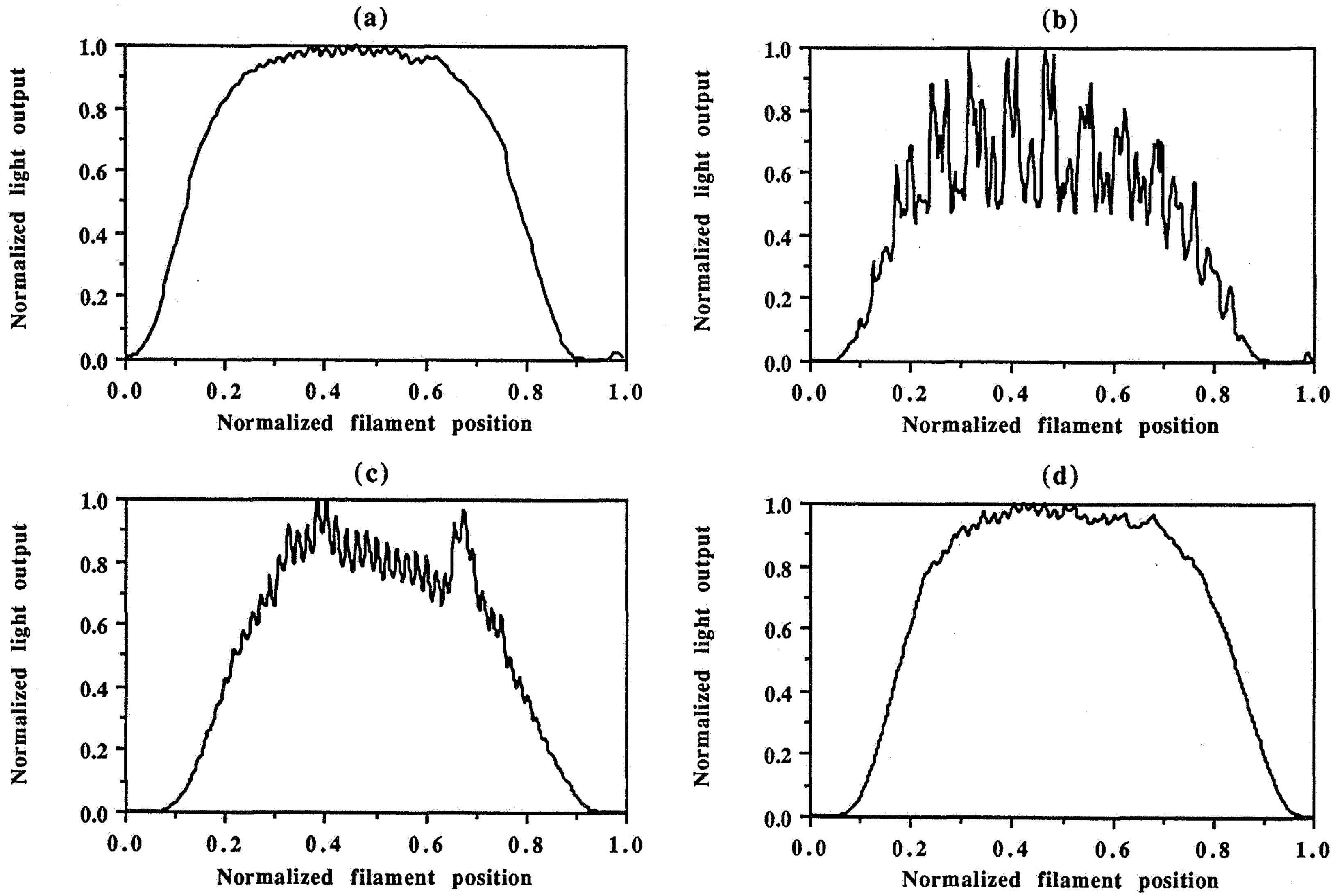
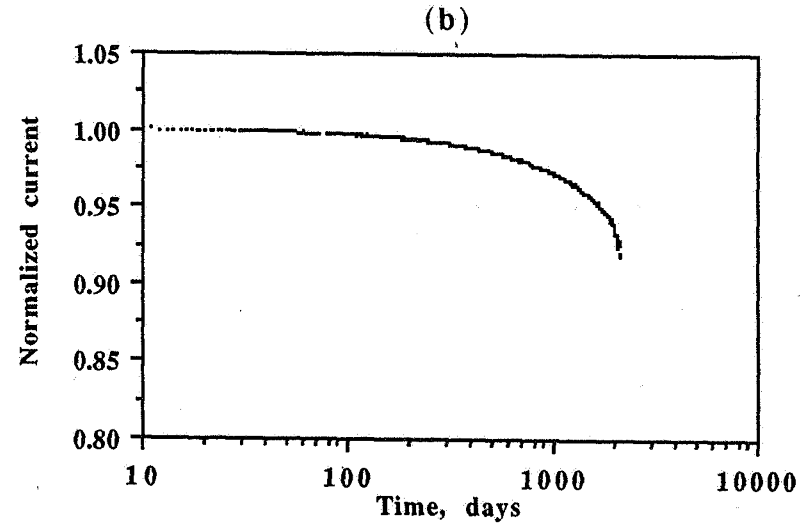
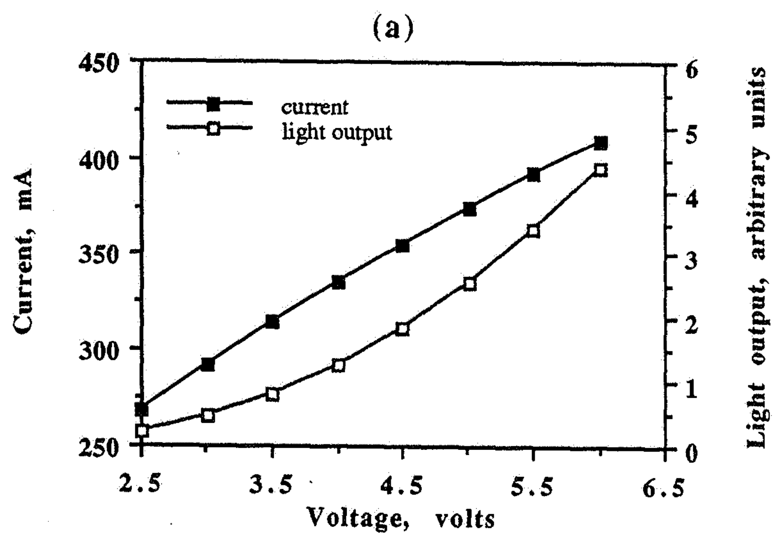


Figure A34. Lamp #2 of Experiment #4. These graphs show the light output from the lamp as a function of location along the filament. (a) 106 days of operation. (b) 590 days of operation. (c) 1023 days of operation. (d) 1476 days of operation.

SBRC part number: 54967-2 (EO 6086A)
Filament material: GE 3D-EESM
Filament diameter: 38.8 µm
Filament length: 3.485 mm
Number of turns: 55
Post contact technique: brazed
Operating voltage: 3.552 volts +0.006,-0.011
Burn-in time: none





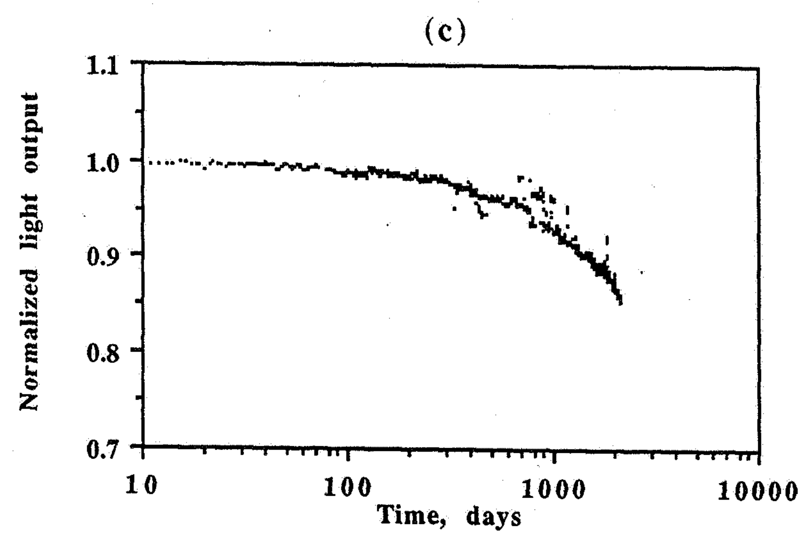


Figure A35. Lamp #3 of Experiment #4. This lamp burned-out after 2100 days of operation. (a) Pre-life test characterization of the lamp. Lamp light output and current vs. voltage. (b) Lamp current vs. days of operation. (c) Lamp light output vs. days of operation.

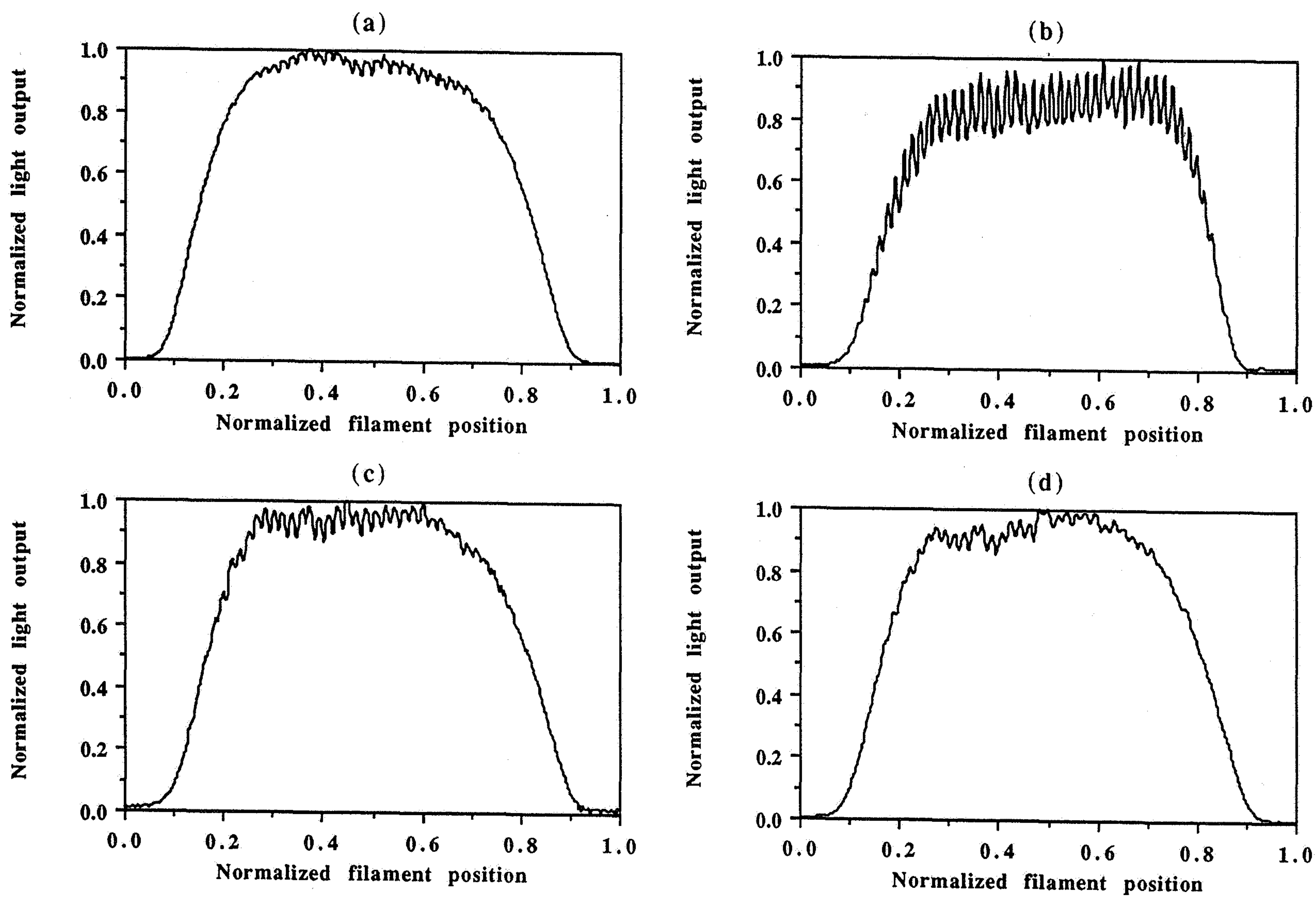
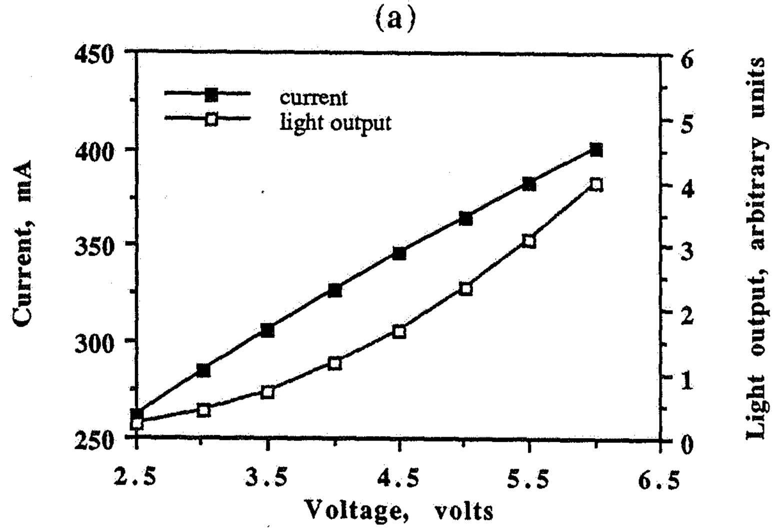
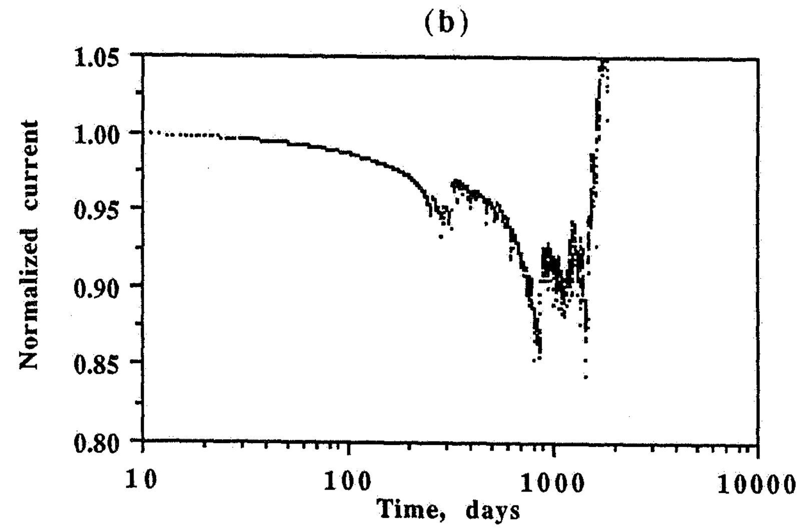


Figure A36. Lamp #3 of Experiment #4. These graphs show the light output from the lamp as a function of location along the filament. (a) 46 days of operation. (b) 432 days of operation. (c) 789 days of operation. (d) 1144 days of operation.

SBRC part number: 54967-2 (EO 6086A)
Filament material: GE 3D-EESM
Filament diameter: 39.2 μm
Filament length: 3.526 mm
Number of turns: 57
Post contact technique: brazed
Operating voltage: 4.688 volts +0.008,-0.017
Burn-in time: none





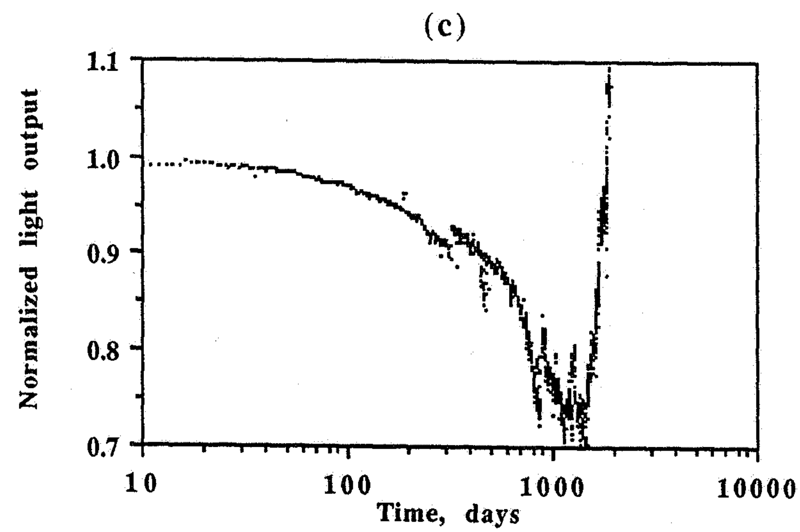


Figure A37. Lamp #4 of Experiment #4. This lamp burned-out after 2101 days of operation. (a) Pre-life test characterization of the lamp. Lamp light output and current vs. voltage. (b) Lamp current vs. days of operation. (c) Lamp light output vs. days of operation.

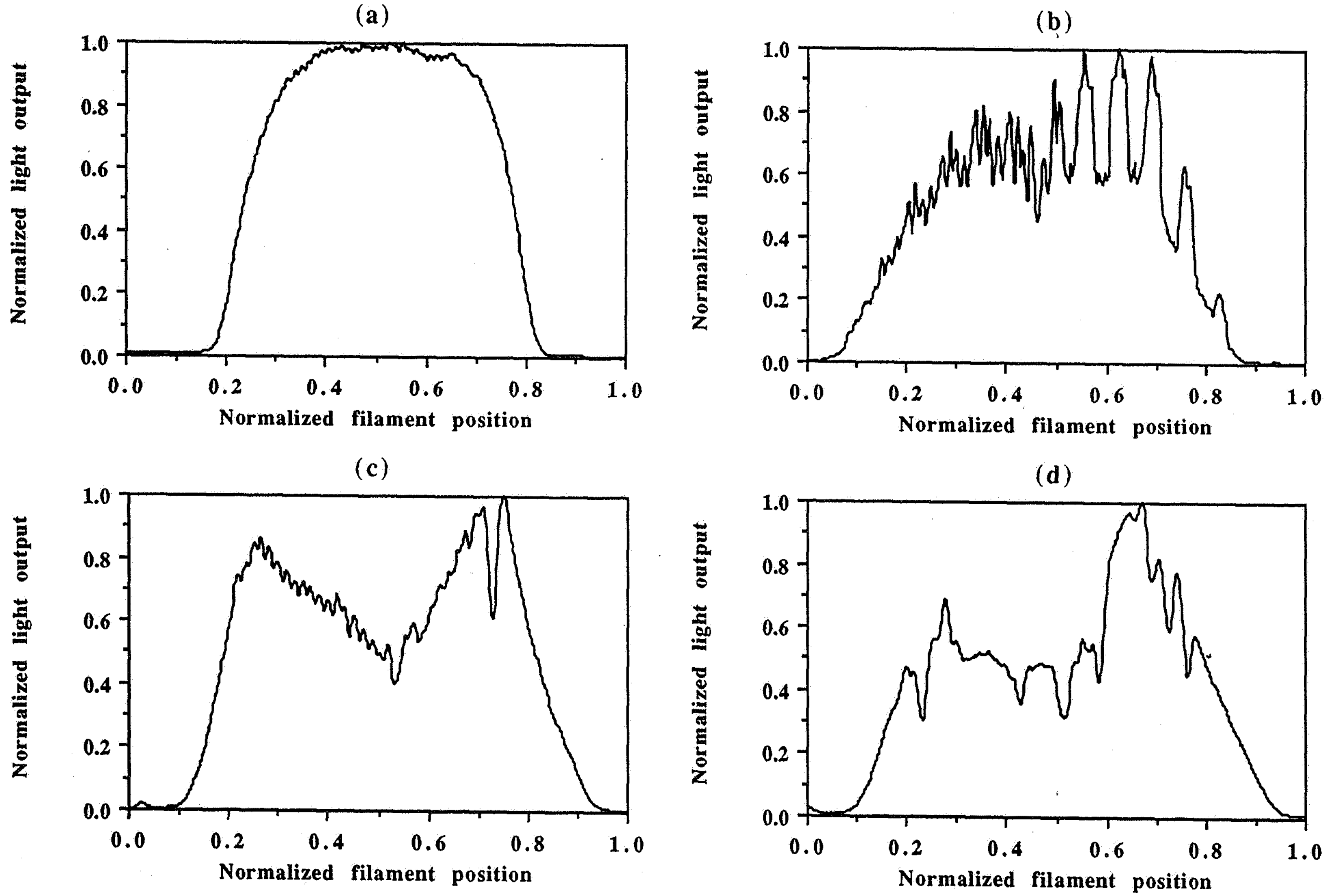
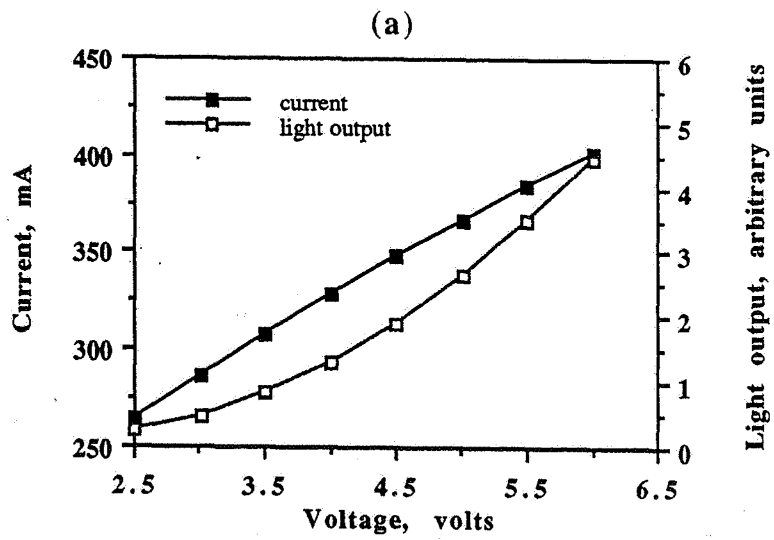


Figure A38. Lamp #4 of Experiment #4. These graphs show the light output from the lamp as a function of location along the filament. Severe distortion of the filament occurred during the life test. (a) 2 days of operation. (b) 418 days of operation. (c) 804 days of operation. (d) 1159 days of operation.

SBRC part number: 54967-2 (EO 6086A)
Filament material: GE 3D-EESM
Filament diameter: 38.8 µm
Filament length: 3.611 mm
Number of turns: 57
Post contact technique: brazed
Operating voltage: 4.676 volts +0.015,-0.008
Burn-in time: none



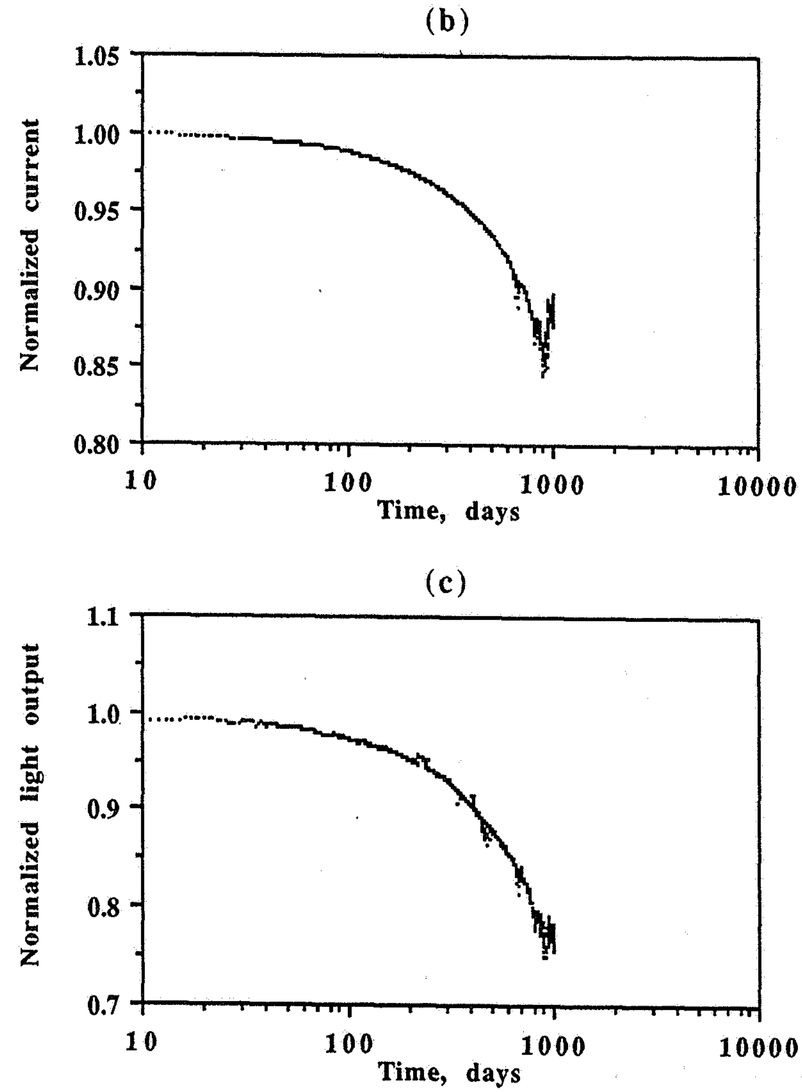


Figure A39. Lamp #5 of Experiment #4. This lamp burned-out after 1016 days of operation. (a) Pre-life test characterization of the lamp. Lamp light output and current vs. voltage. (b) Lamp current vs. days of operation. (c) Lamp light output vs. days of operation.

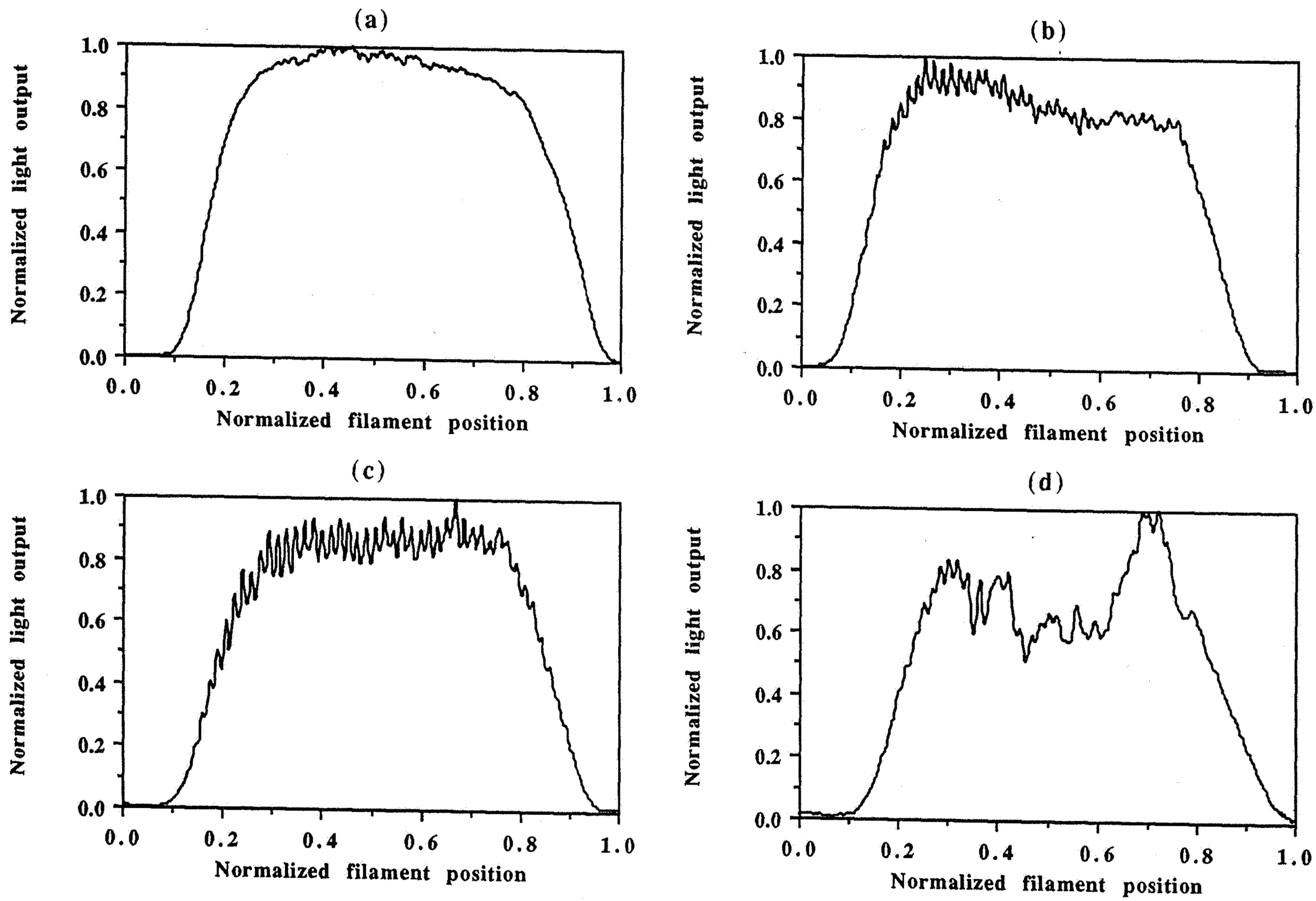


Figure A40. Lamp #5 of Experiment #4. These graphs show the light output from the lamp as a function of location along the filament. Severe distortion of the filament occurred during the life test. (a) 61 days of operation. (b) 373 days of operation. (c) 670 days of operation. (d) 978 days of operation.

SBRC part number: 54967-2 (EO 6086A)
Filament material: GE 3D-EESM
Filament diameter: 38.7 μm
Filament length: 3.442 mm
Number of turns: 52
Post contact technique: brazed
Operating voltage: 4.678 volts +0.004,-0.006
Burn-in time: none

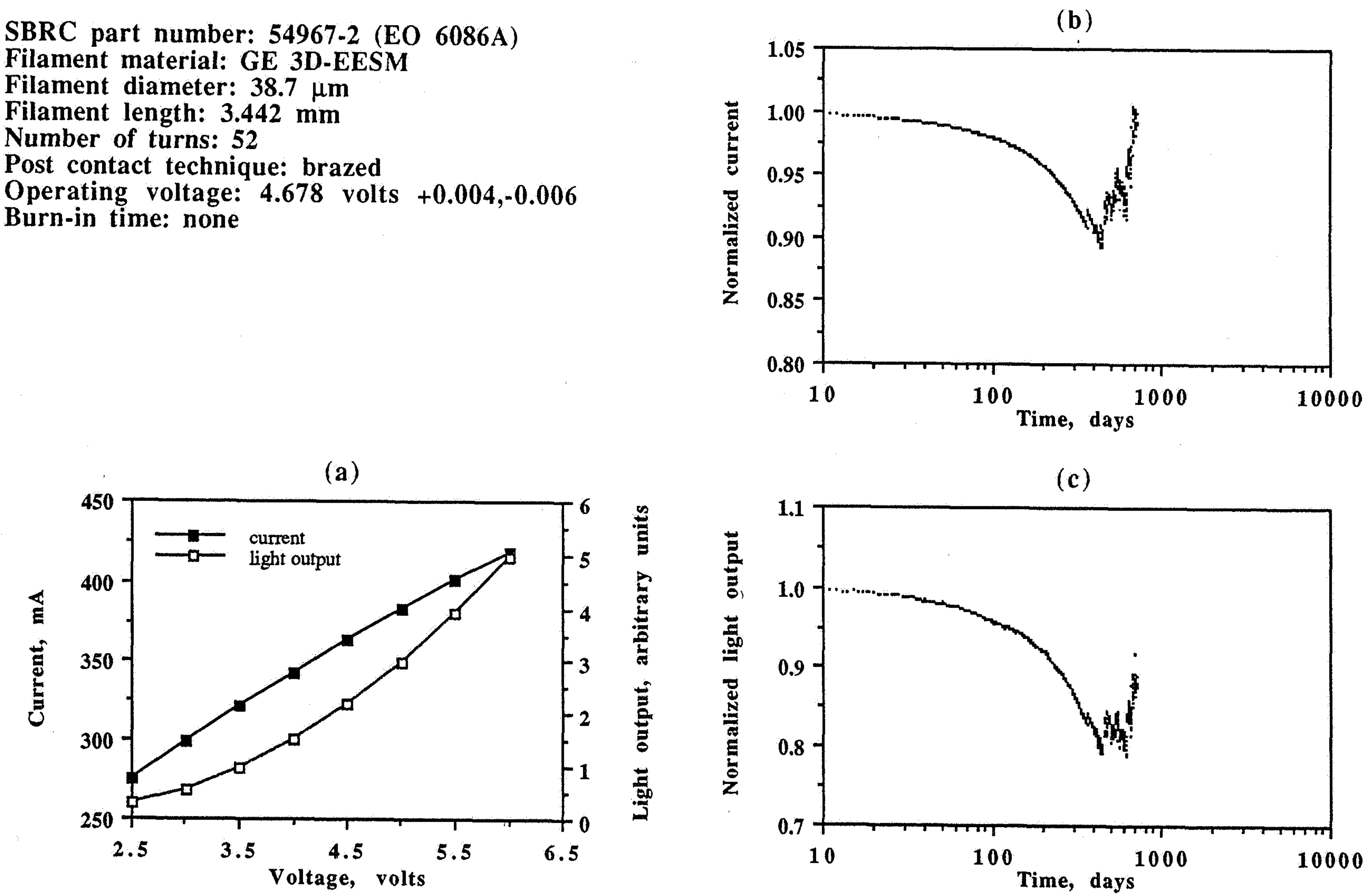


Figure A41. Lamp #6 of Experiment #4. This lamp burned-out after 715 days of operation. (a) Pre-life test characterization of the lamp. Lamp light output and current vs. voltage. (b) Lamp current vs. days of operation. (c) Lamp light output vs. days of operation.

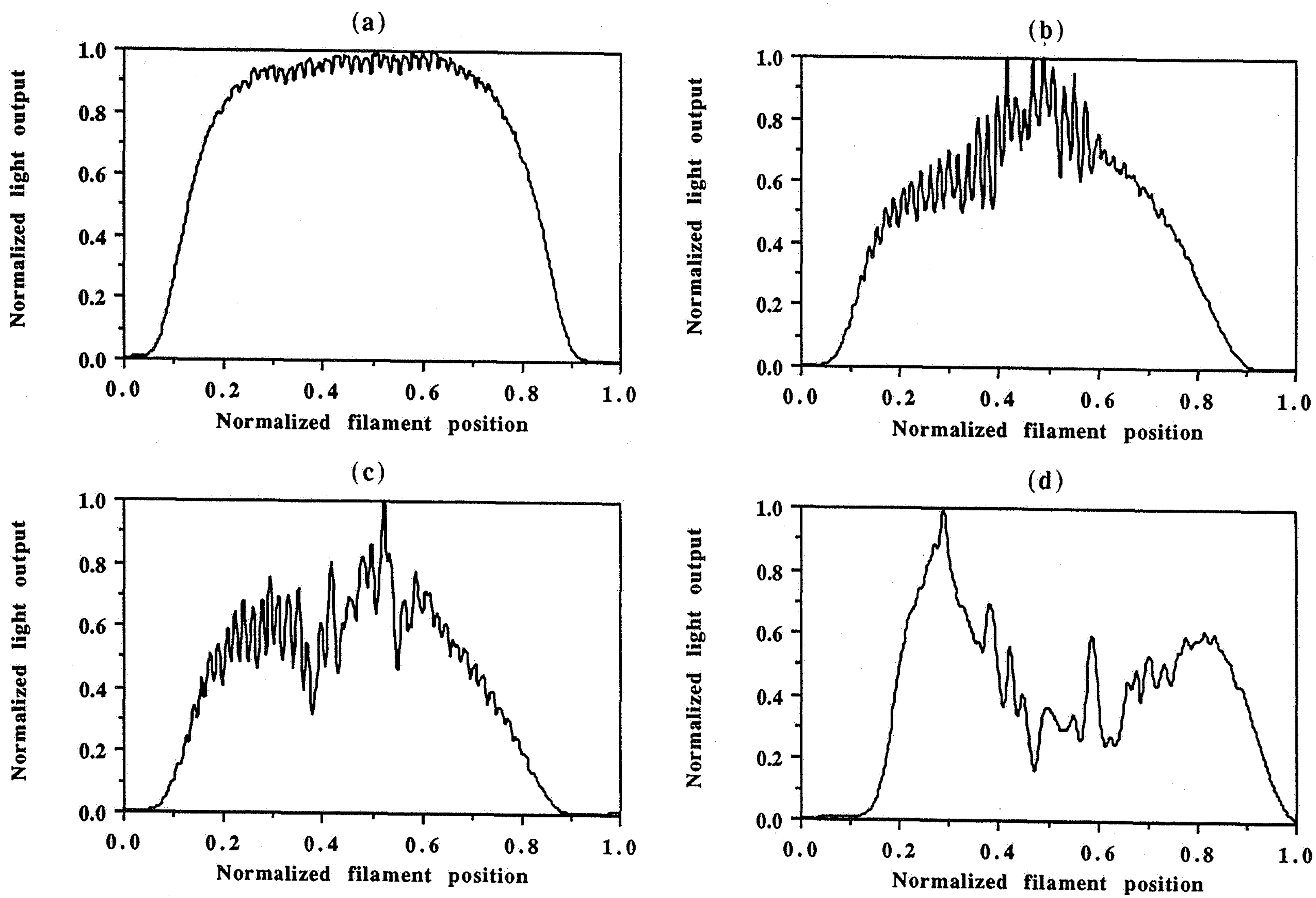


Figure A42. Lamp #6 of Experiment #4. These graphs show the light output from the lamp as a function of location along the filament. Severe distortion of the filament occurred during the life test. (a) 39 days of operation. (b) 251 days of operation. (c) 452 days of operation. (d) 711 days of operation.

SBRC part number: 54967-2 (Lot F-2)
Filament material: GE 3D-EESM
Filament diameter: not measured
Filament length: not measured
Number of turns: not measured
Post contact technique: brazed
Operating voltage: 5.032 volts +0.003,-0.018
Burn-in time: none

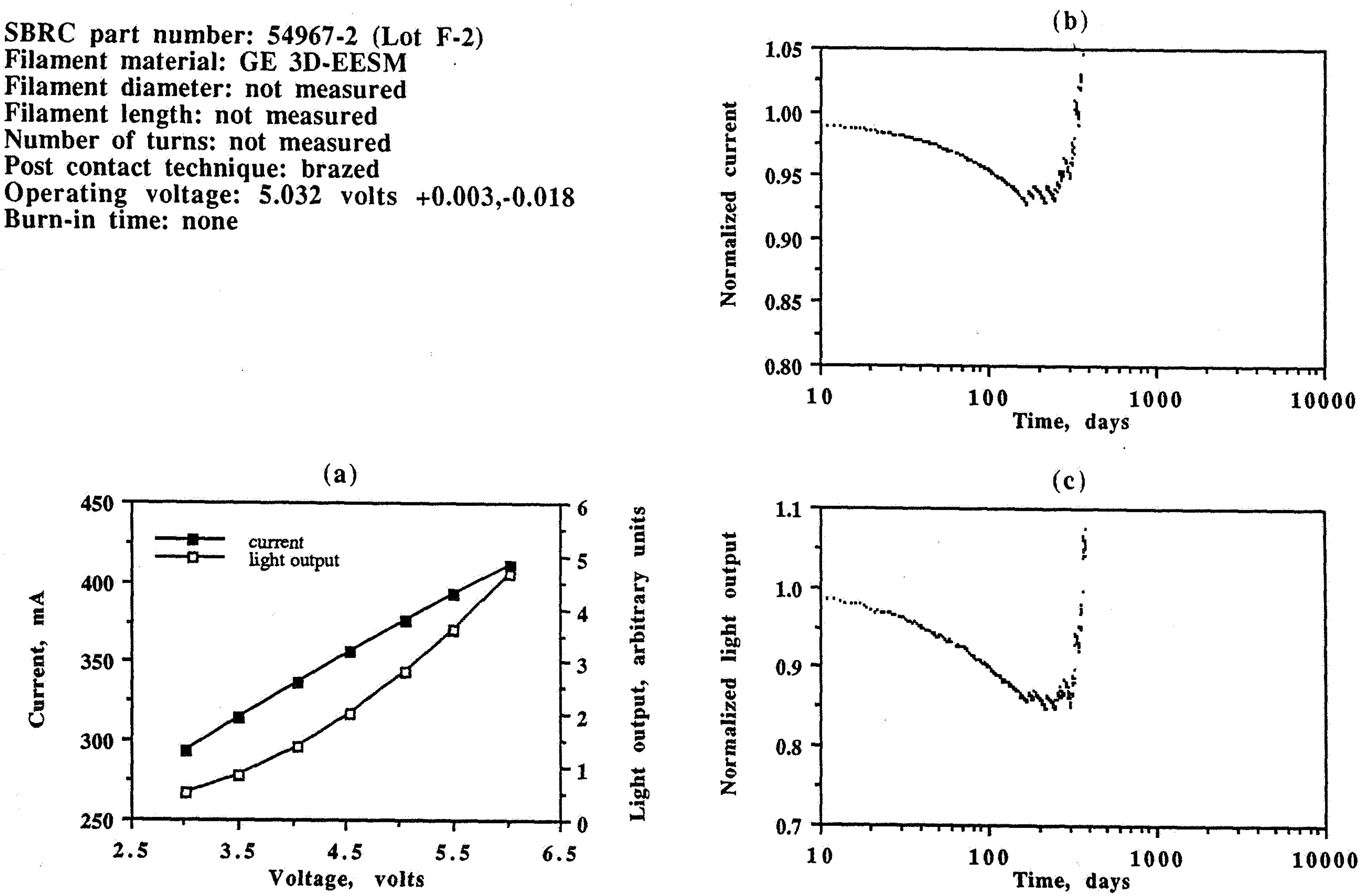


Figure A43. Lamp #7 of Experiment #4. This lamp burned-out after 378 days of operation. This lamp would have passed the burn in test (0.62% decrease in current). (a) Pre-life test characterization of the lamp. Lamp light output and current vs. voltage. (b) Lamp current vs. days of operation. (c) Lamp light output vs. days of operation.

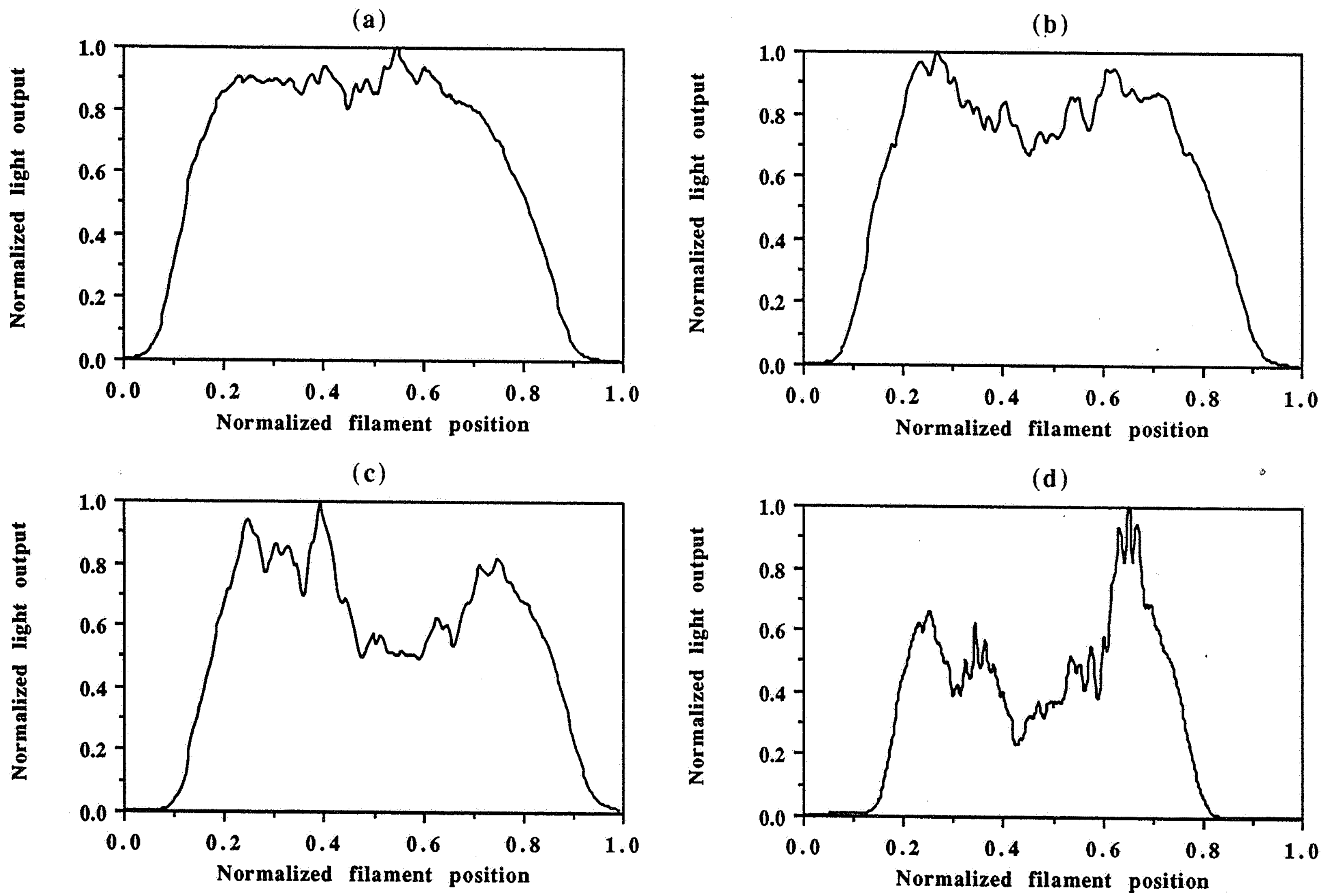
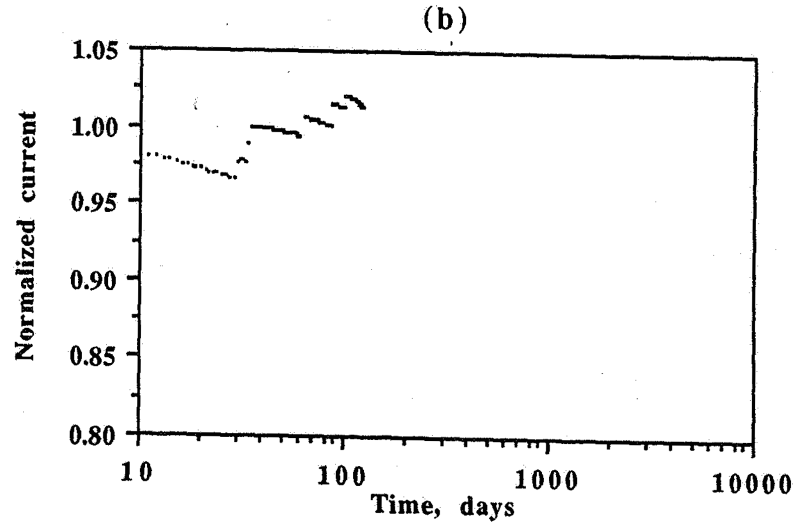
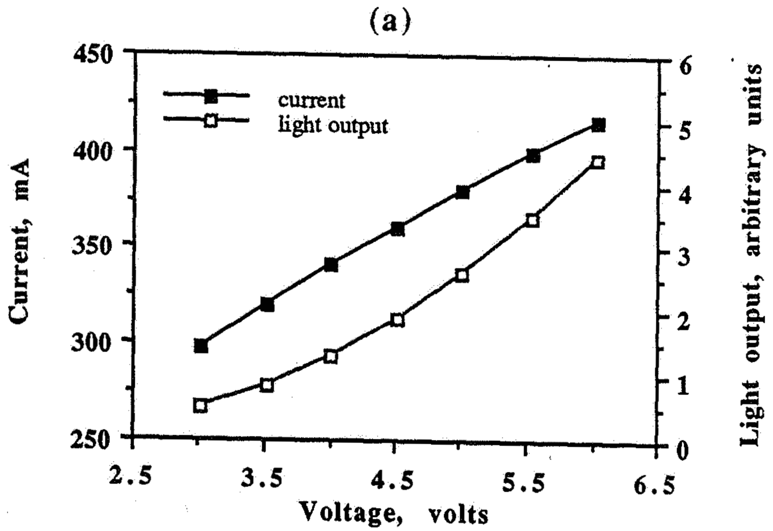


Figure A44. Lamp #7 of Experiment #4. These graphs show the light output from the lamp as a function of location along the filament. Severe distortion of the filament occurred during the life test. (a) 106 days of operation. (b) 211 days of operation. (c) 263 days of operation. (d) 321 days of operation.

SBRC part number: 54967-2 (Lot F-2)
Filament material: GE 3D-EESM
Filament diameter: 38.2 μm
Filament length: not measured
Number of turns: not measured
Post contact technique: brazed
Operating voltage: 5.008 volts +0.008,-0.002
Burn-in time: none





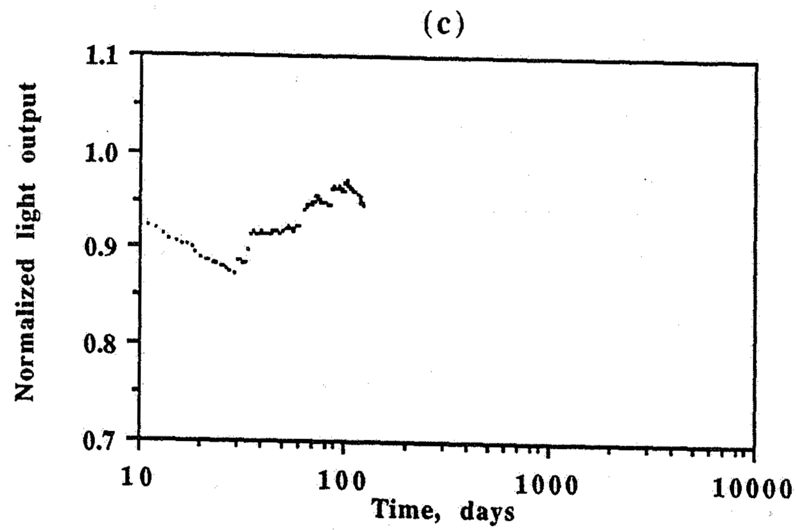


Figure A45. Lamp #8 of Experiment #4. The life test for this lamp was discontinued after 123 days to examine the severe distortions occurring to the filament. This lamp would have failed the burn in test (1.42% decrease in current). (a) Pre-life test characterization of the lamp. Lamp light output and current vs. voltage. (b) Lamp current vs. days of operation. (c) Lamp light output vs. days of operation.

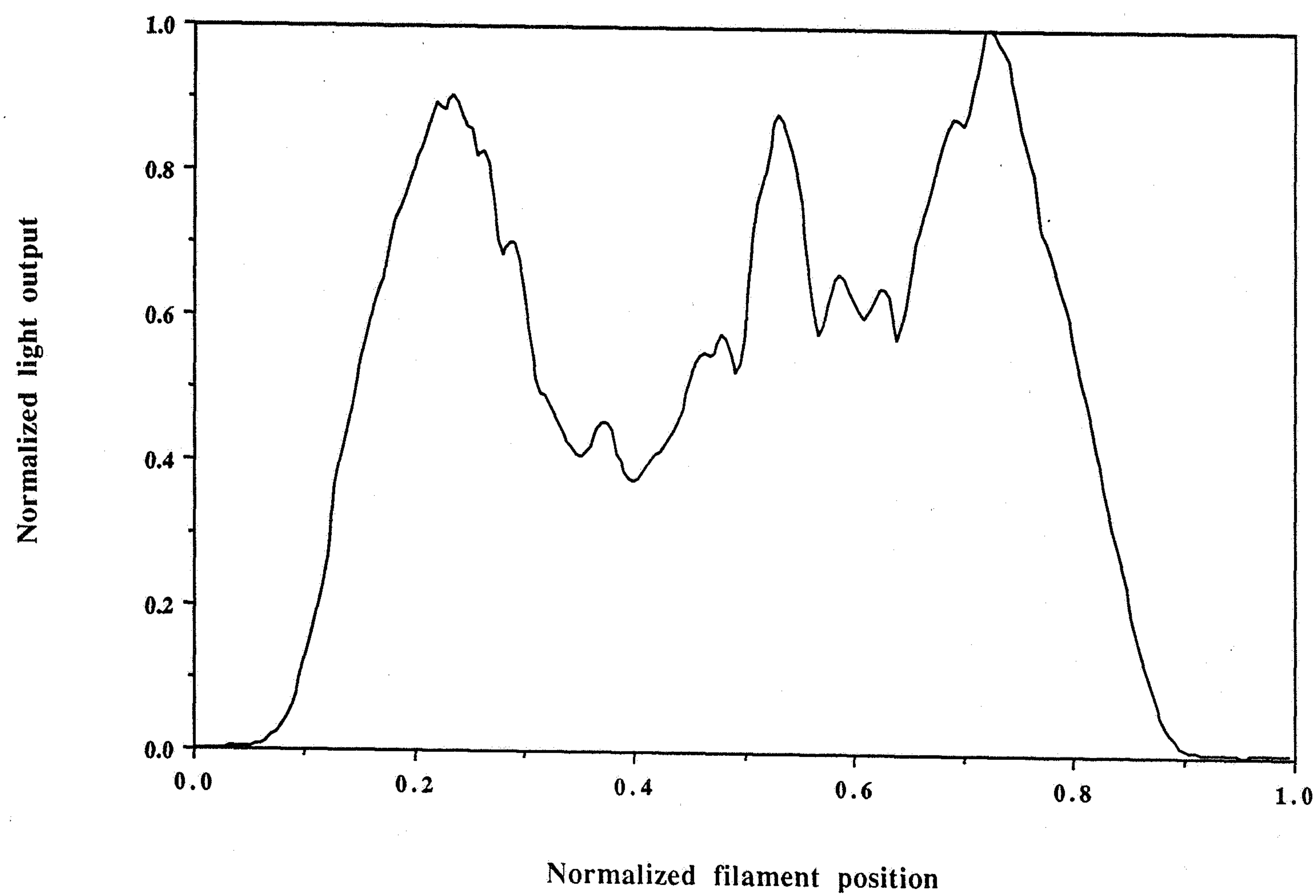
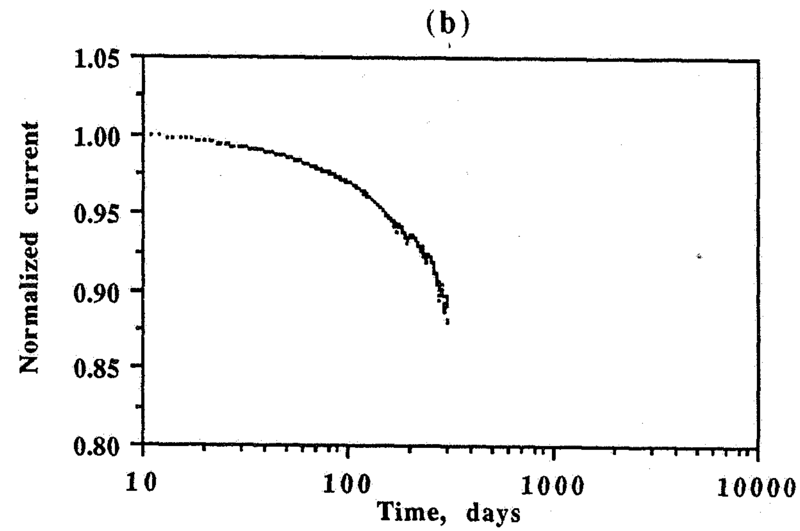
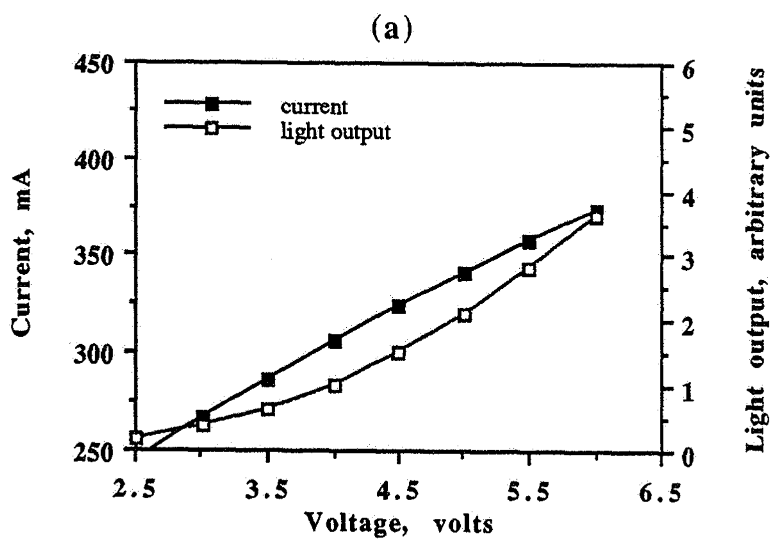


Figure A46. Lamp #8 of Experiment #4. This graph shows the light output from the lamp as a function of location along the filament after 106 days of operation. Severe distortion of the filament occurred during the life test.

SBRC part number: 54967-2 (EO 6068A)
Filament material: GE 3D-EESM
Filament diameter: not measured
Filament length: 3.633 mm
Number of turns: 62
Post contact technique: brazed
Operating voltage: 5.011 volts +0.001,-0.008
Burn-in time: none





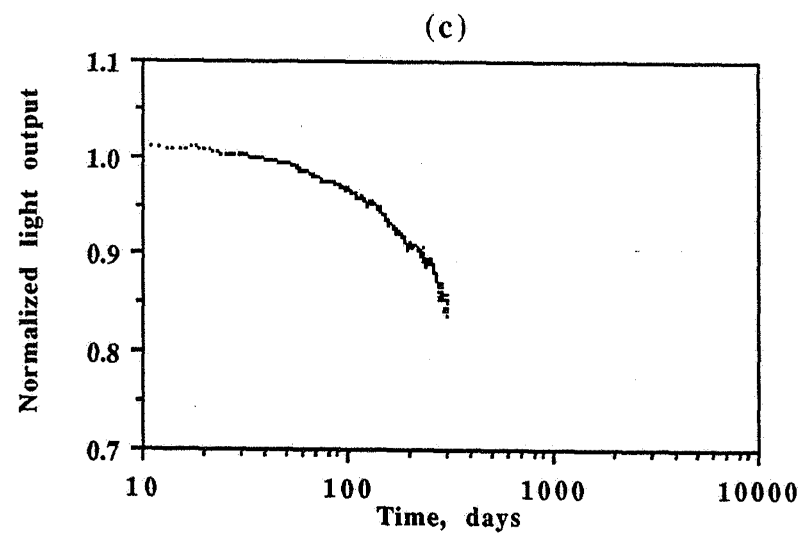


Figure A47. Lamp #9 of Experiment #4. This lamp burned-out after 307 days of operation. This lamp would have passed the burn in test (0.42% decrease in current). (a) Pre-life test characterization of the lamp. Lamp light output and current vs. voltage. (b) Lamp current vs. days of operation. (c) Lamp light output vs. days of operation.

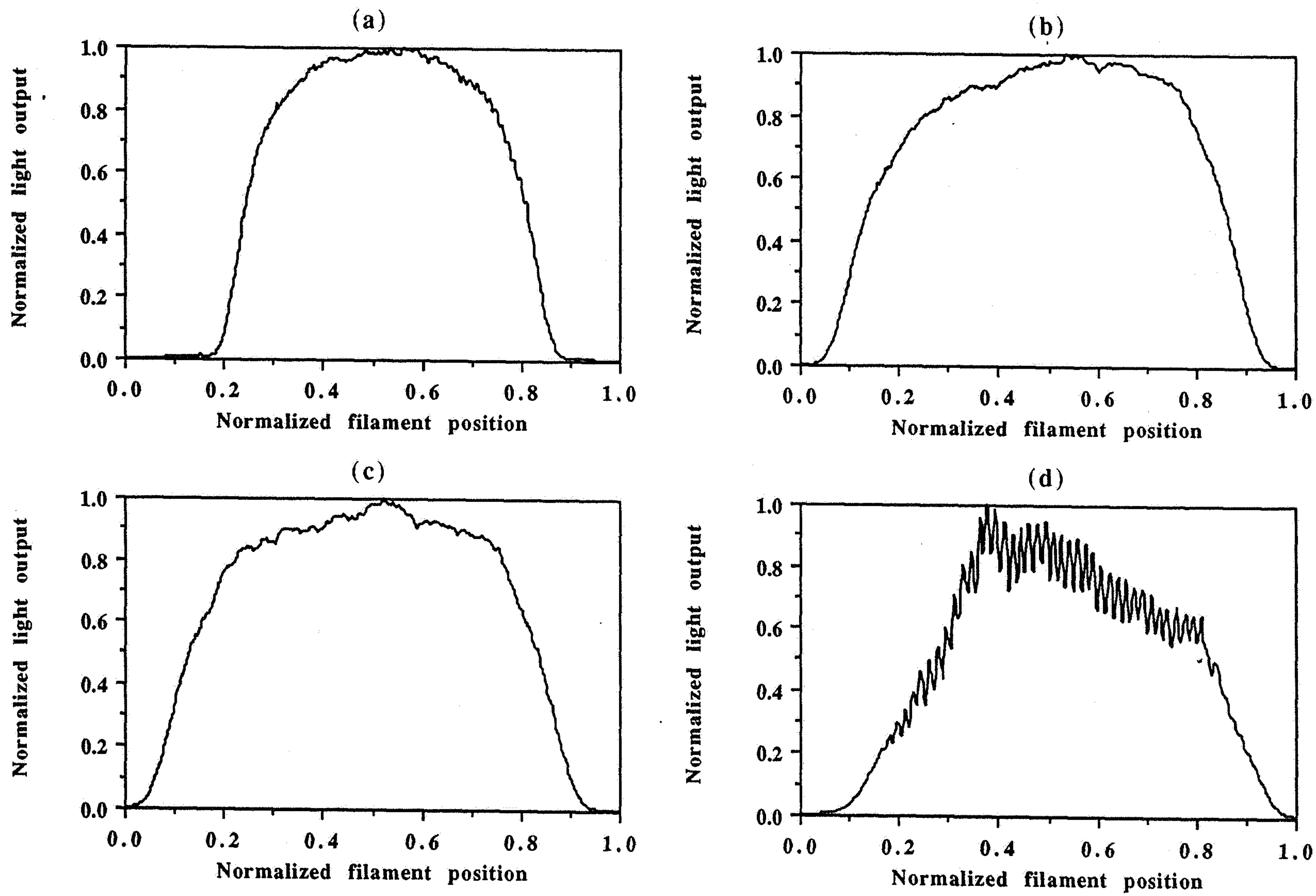


Figure A48. Lamp #9 of Experiment #4. These graphs show the light output from the lamp as a function of location along the filament. (a) 2 days of operation. (b) 61 days of operation. (c) 122 days of operation. (d) 303 days of operation.

SBRC part number: 54967-1 (Lot F-2)
Filament material: GE NF-EPSM
Filament diameter: not measured
Filament length: not measured
Number of turns: not measured
Post contact technique: brazed
Operating voltage: 3.551 volts +0.006,-0.013
Burn-in time: none

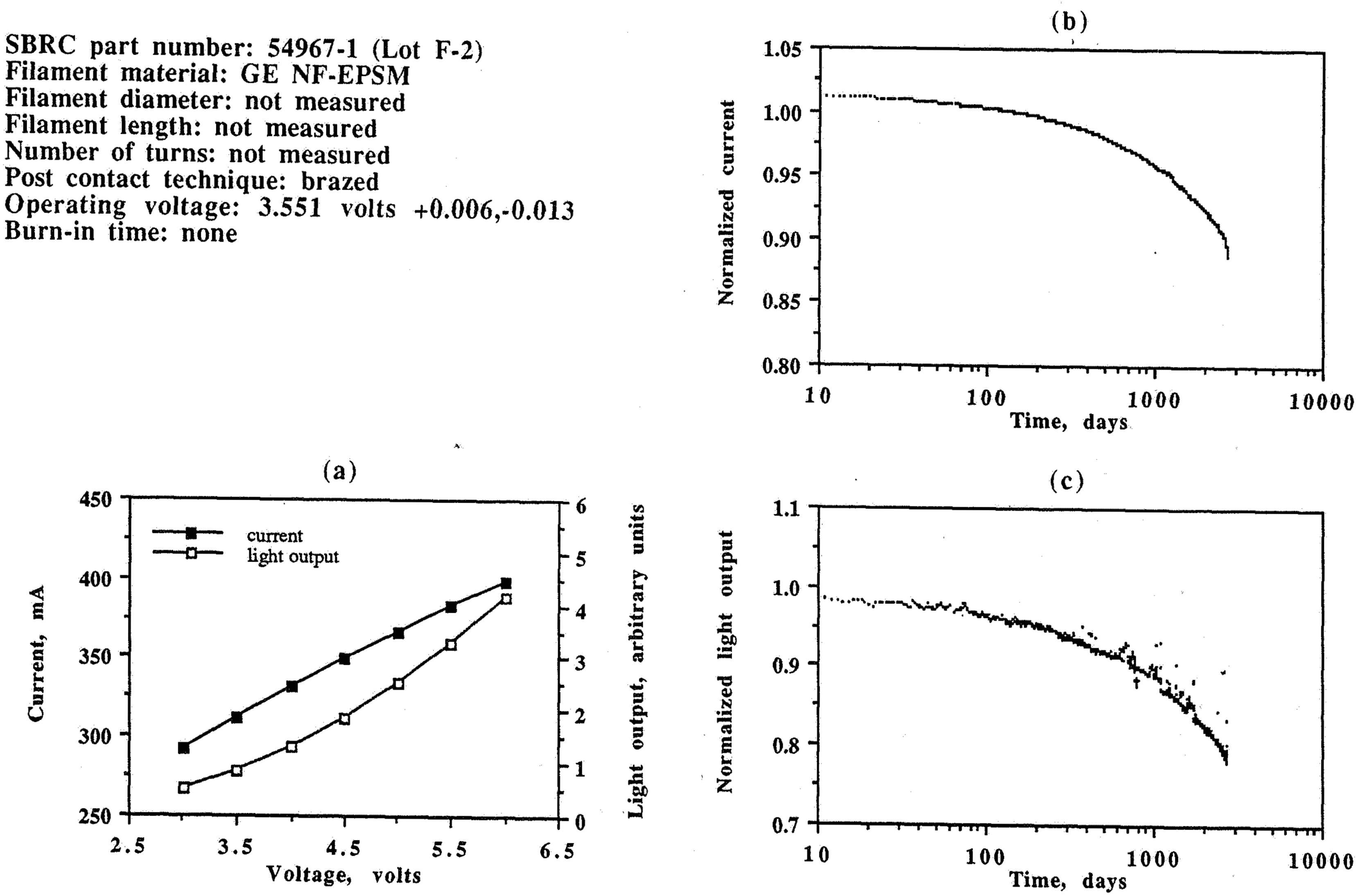


Figure A49. Lamp #10 of Experiment #4. This lamp was still operating after 2700 days. (a) Pre-life test characterization of the lamp. Lamp light output and current vs. voltage. (b) Lamp current vs. days of operation. (c) Lamp light output vs. days of operation.

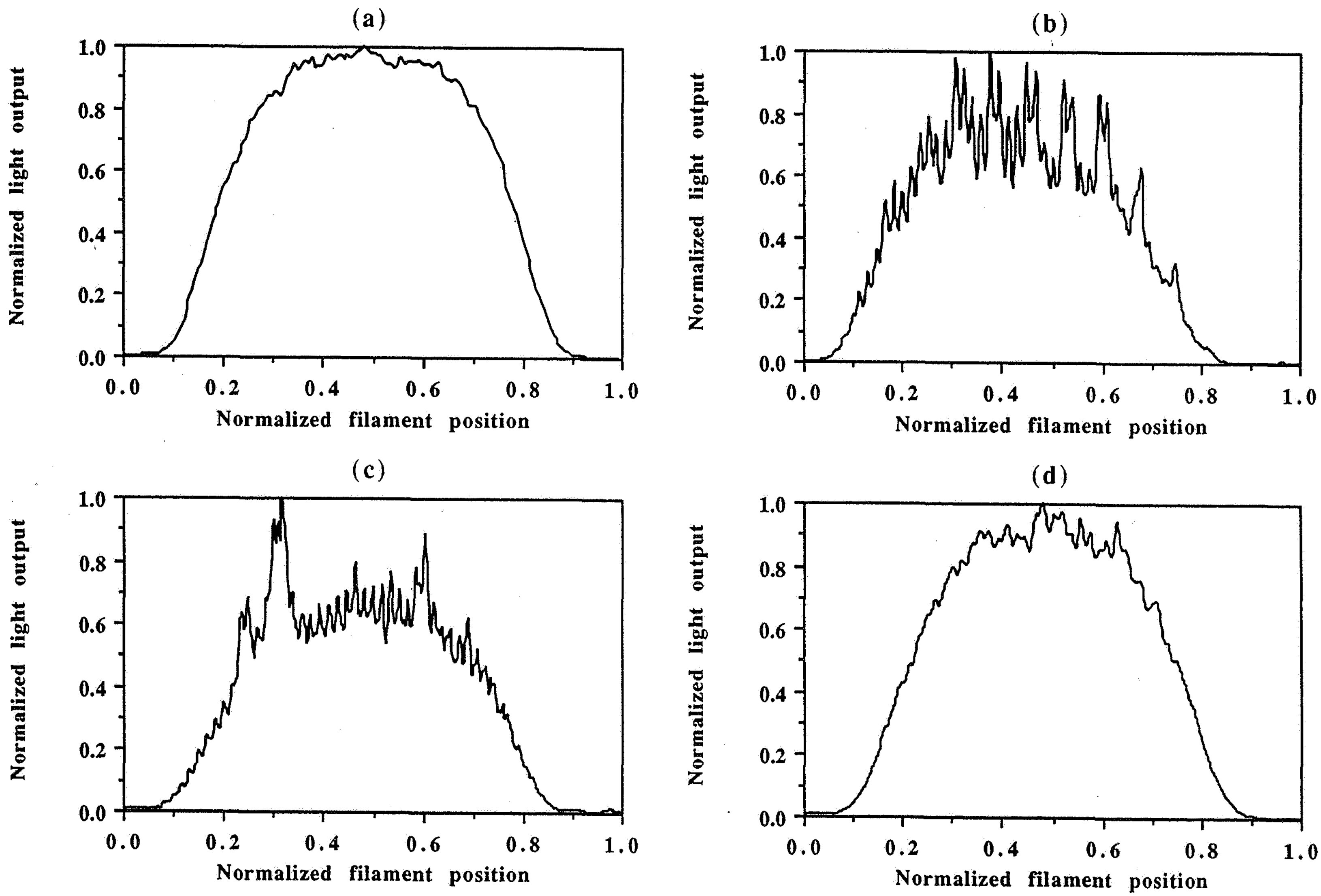


Figure A50. Lamp #10 of Experiment #4. These graphs show the light output from the lamp as a function of location along the filament. (a) 106 days of operation. (b) 590 days of operation. (c) 1023 days of operation. (d) 1476 days of operation.

SBRC part number: 54967-1 (Lot F-2)
Filament material: GE NF-EPSM
Filament diameter: 38.7 µm
Filament length: 3.339 mm
Number of turns: 59
Post contact technique: brazed
Operating voltage: 3.553 volts +0.004,-0.008
Burn-in time: none

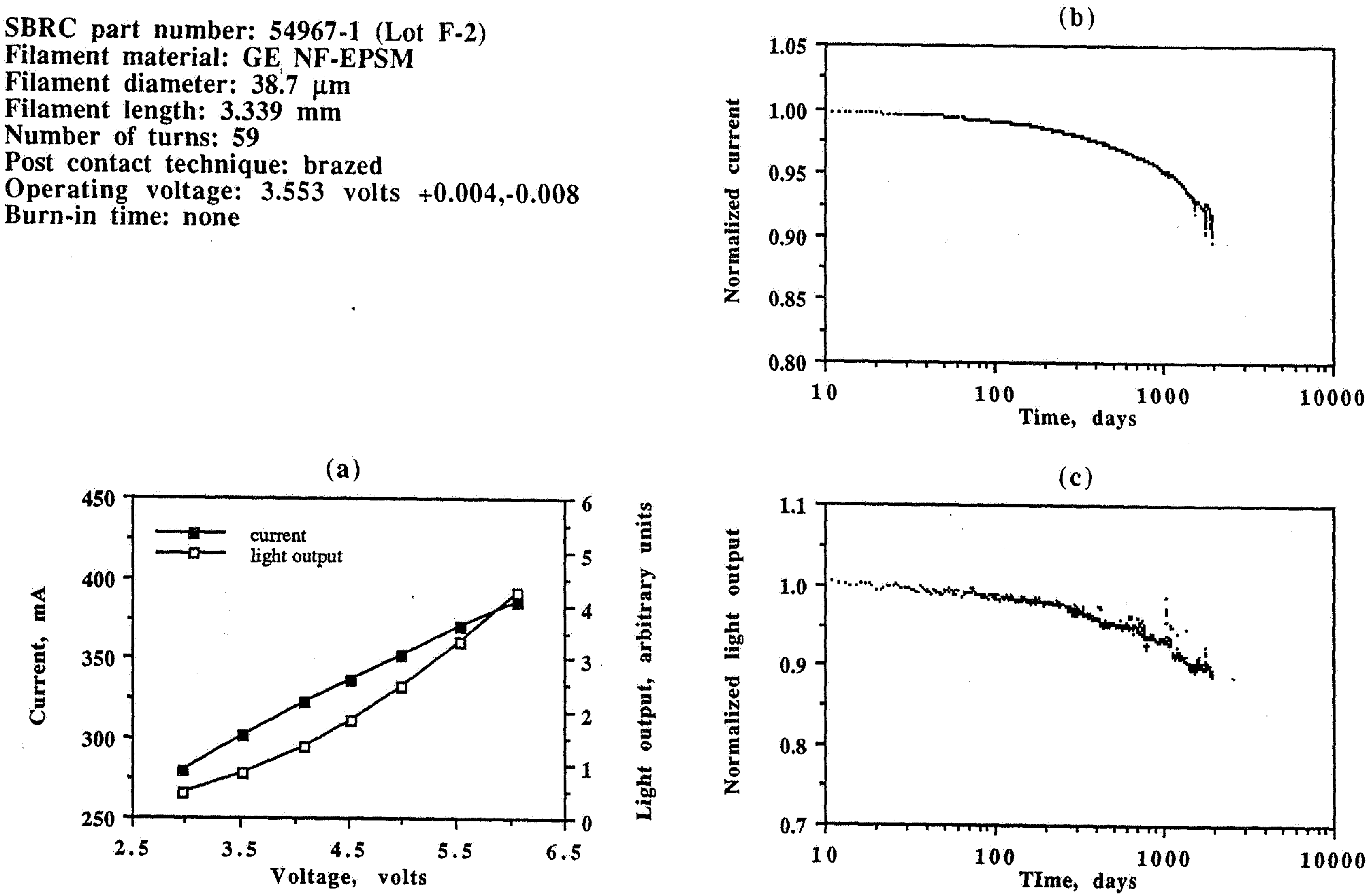


Figure A51. Lamp #11 of Experiment #4. This lamp burned-out after 1949 days of operation. (a) Pre-life test characterization of the lamp. Lamp light output and current vs. voltage. (b) Lamp current vs. days of operation. (c) Lamp light output vs. days of operation.

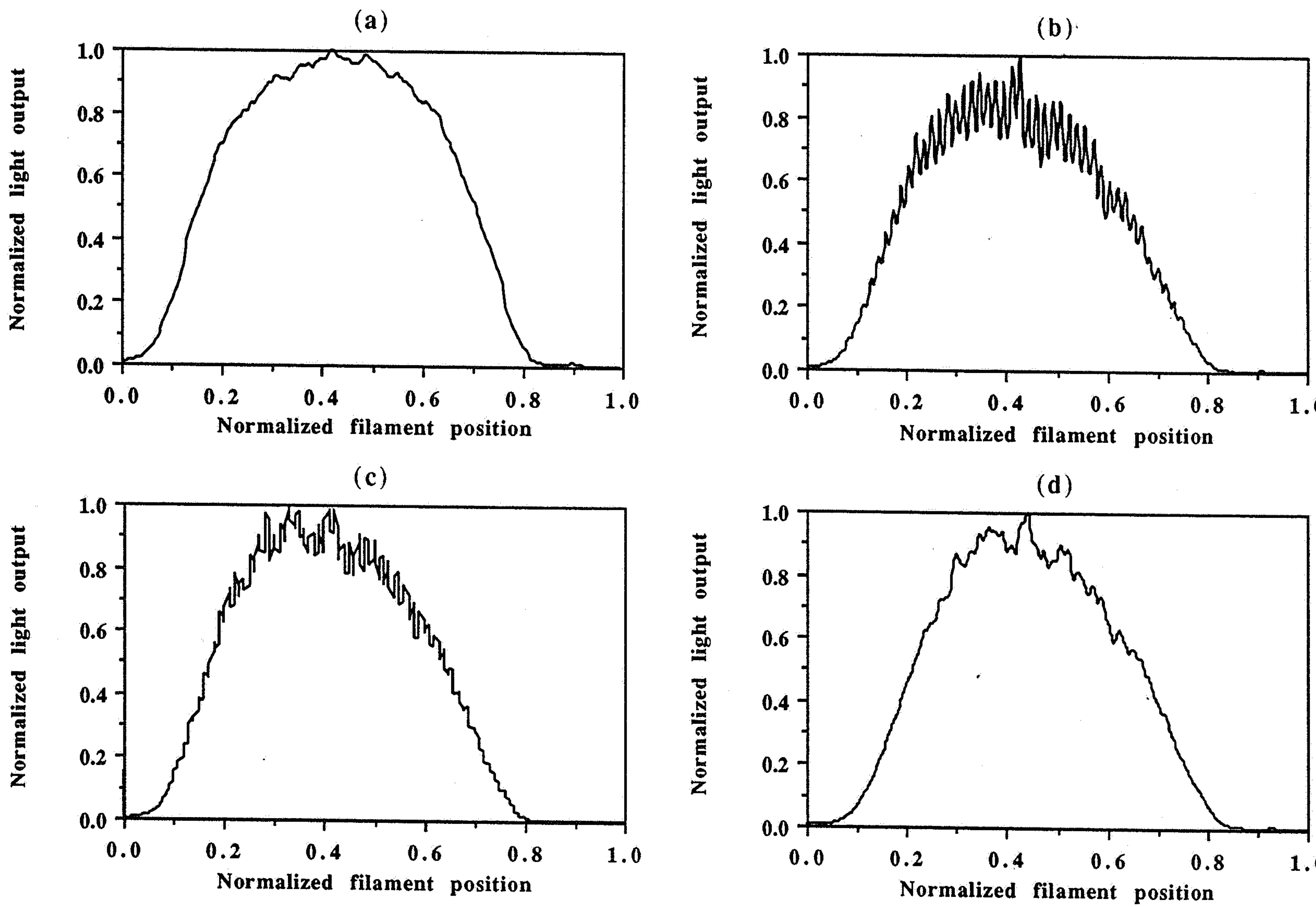
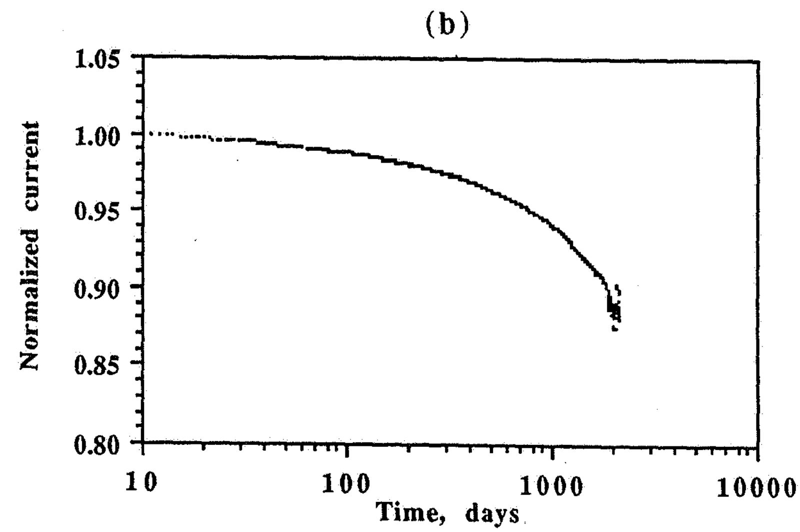
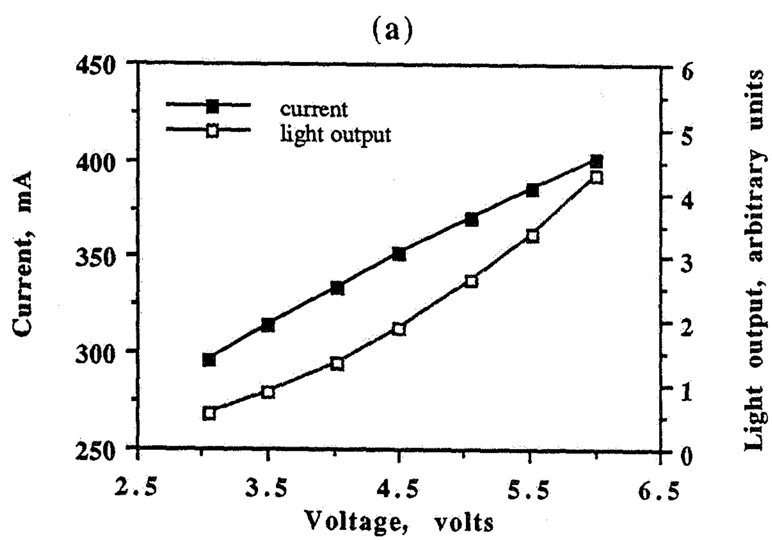


Figure A52. Lamp #11 of Experiment #4. These graphs show the light output from the lamp as a function of location along the filament. (a) 106 days of operation. (b) 590 days of operation. (c) 987 days of operation. (d) 1476 days of operation.

SBRC part number: 54967-1 (Lot F-2)
Filament material: GE NF-EPSM
Filament diameter: 38.4 µm
Filament length: 3.465 mm
Number of turns: 56
Post contact technique: brazed
Operating voltage: 3.549 volts +0.011,-0.013
Burn-in time: none





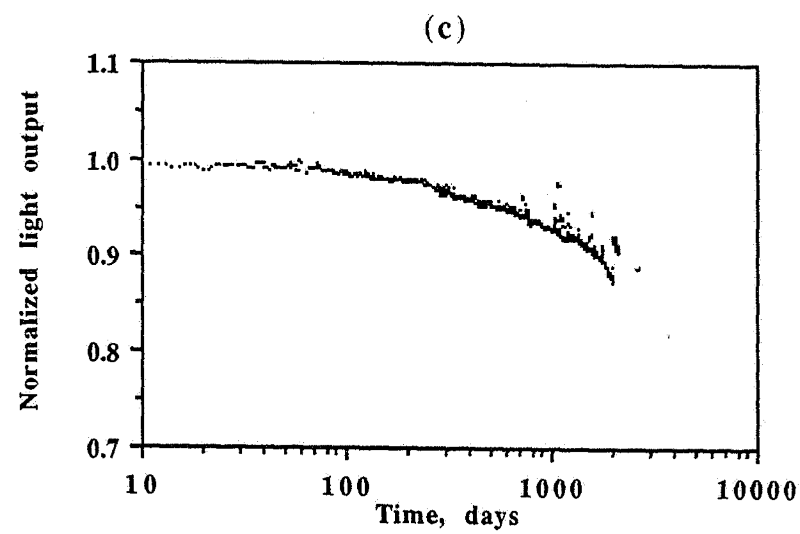


Figure A53. Lamp #12 of Experiment #4. This lamp burned-out after 2103 days of operation. (a) Pre-life test characterization of the lamp. Lamp light output and current vs. voltage. (b) Lamp current vs. days of operation. (c) Lamp light output vs. days of operation.

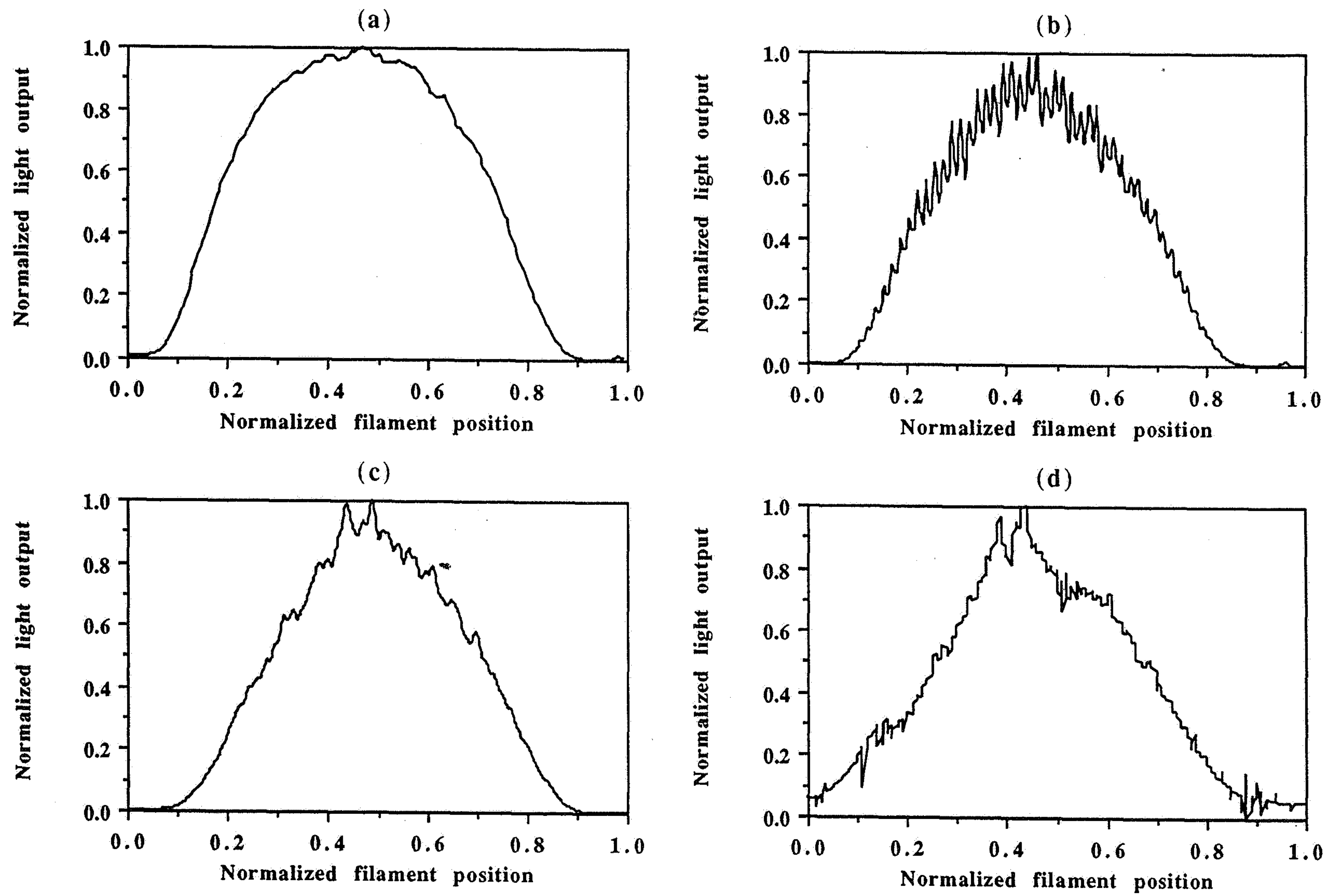
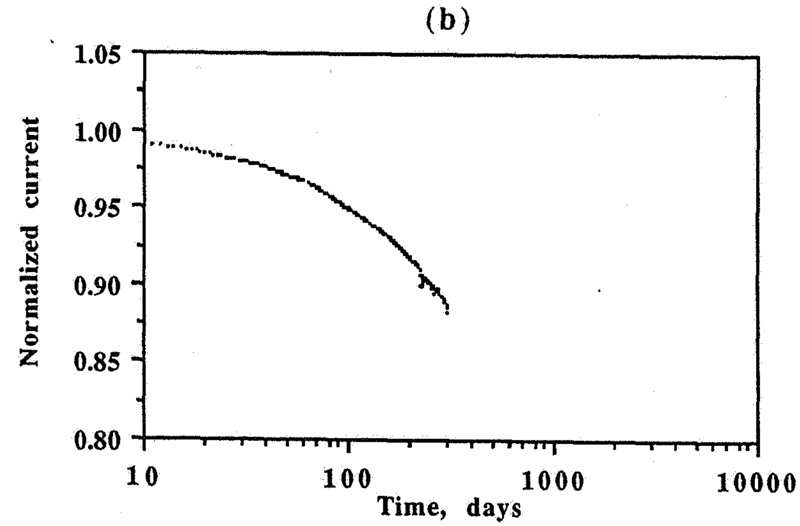
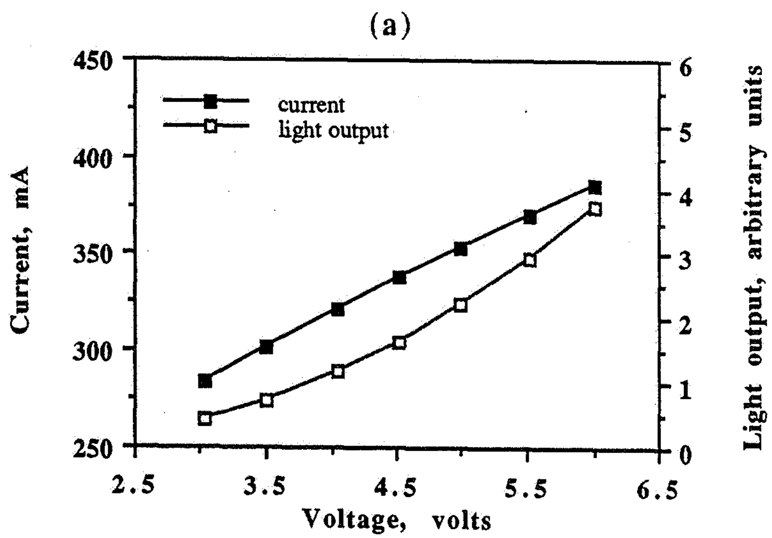


Figure A54. Lamp #12 of Experiment #4. These graphs show the light output from the lamp as a function of location along the filament. (a) 106 days of operation. (b) 791 days of operation. (c) 1476 days of operation. (d) 2081 days of operation.

SBRC part number: 54967-1 (Lot F-2)
Filament material: GE NF-EPSM
Filament diameter: 37.2 μm
Filament length: 3.603 mm
Number of turns: 58
Post contact technique: brazed
Operating voltage: 5.023 volts +0.005,-0.008
Burn-in time: none





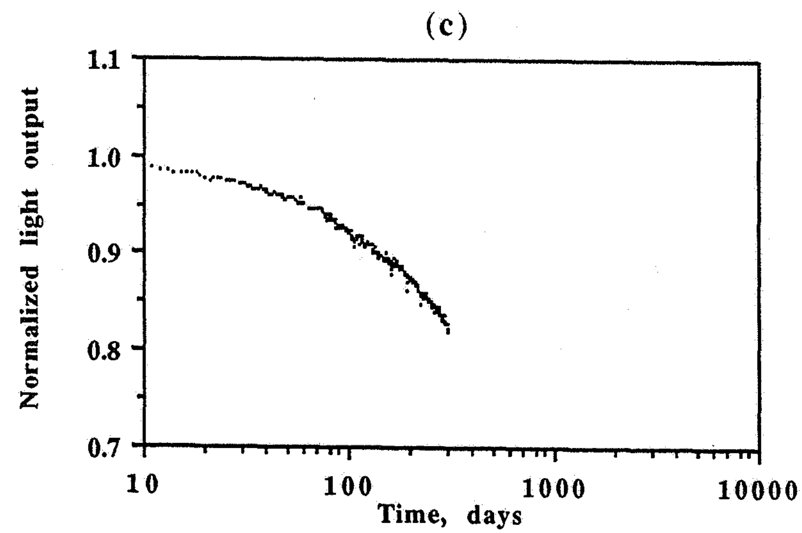


Figure A55. Lamp #16 of Experiment #4. This lamp burned-out after 303 days of operation. This lamp would have passed the burn in test (0.81% decrease in current). (a) Pre-life test characterization of the lamp. Lamp light output and current vs. voltage. (b) Lamp current vs. days of operation. (c) Lamp light output vs. days of operation.

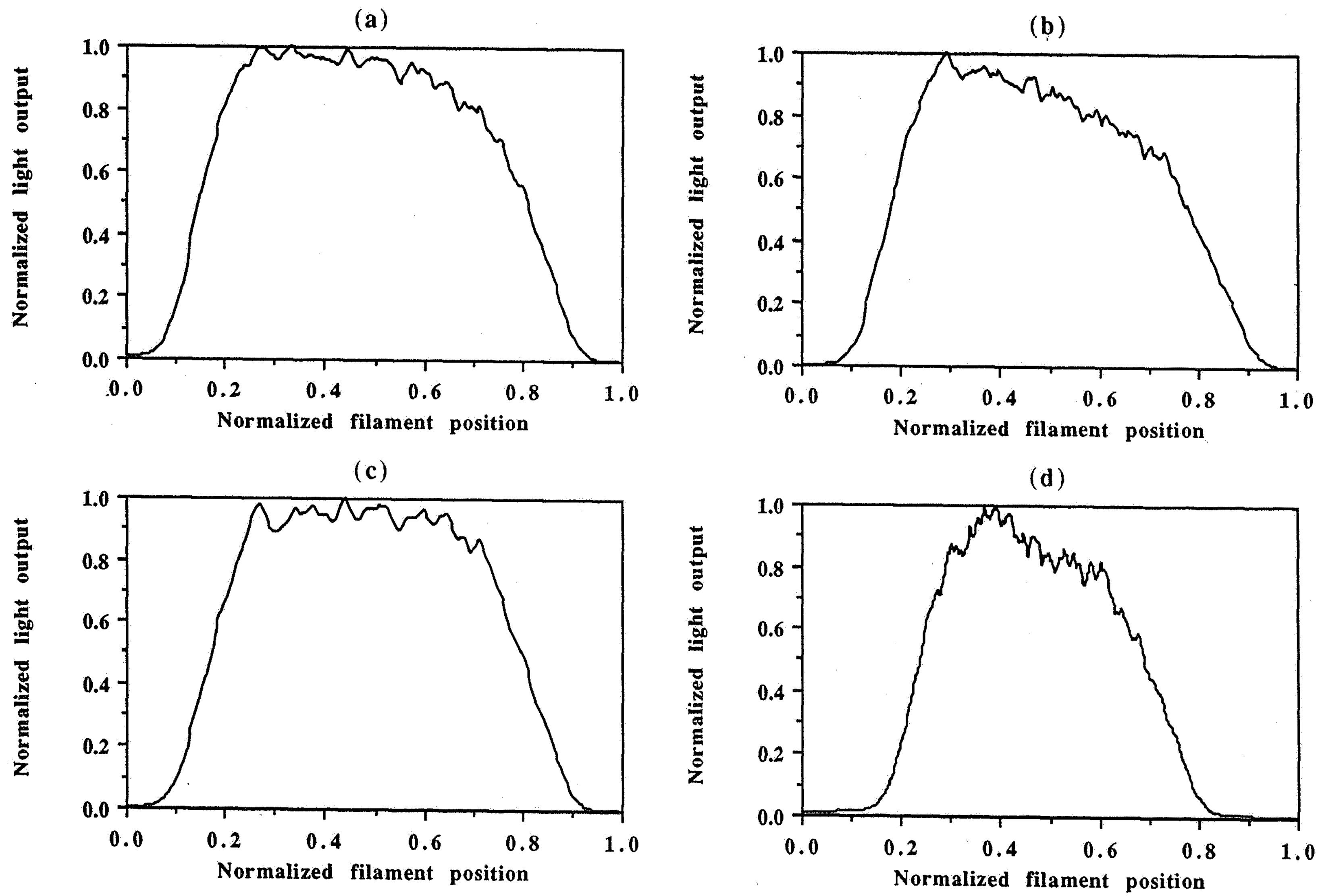


Figure A56. Lamp #16 of Experiment #4. These graphs show the light output from the lamp as a function of location along the filament. (a) 106 days of operation. (b) 211 days of operation. (c) 263 days of operation. (d) 291 days of operation.

SBRC part number: 54967-1 (Lot F-2)
Filament material: GE NF-EPSM
Filament diameter: not measured
Filament length: not measured
Number of turns: not measured
Post contact technique: brazed
Operating voltage: 5.020 volts +0.001,-0.016
Burn-in time: none

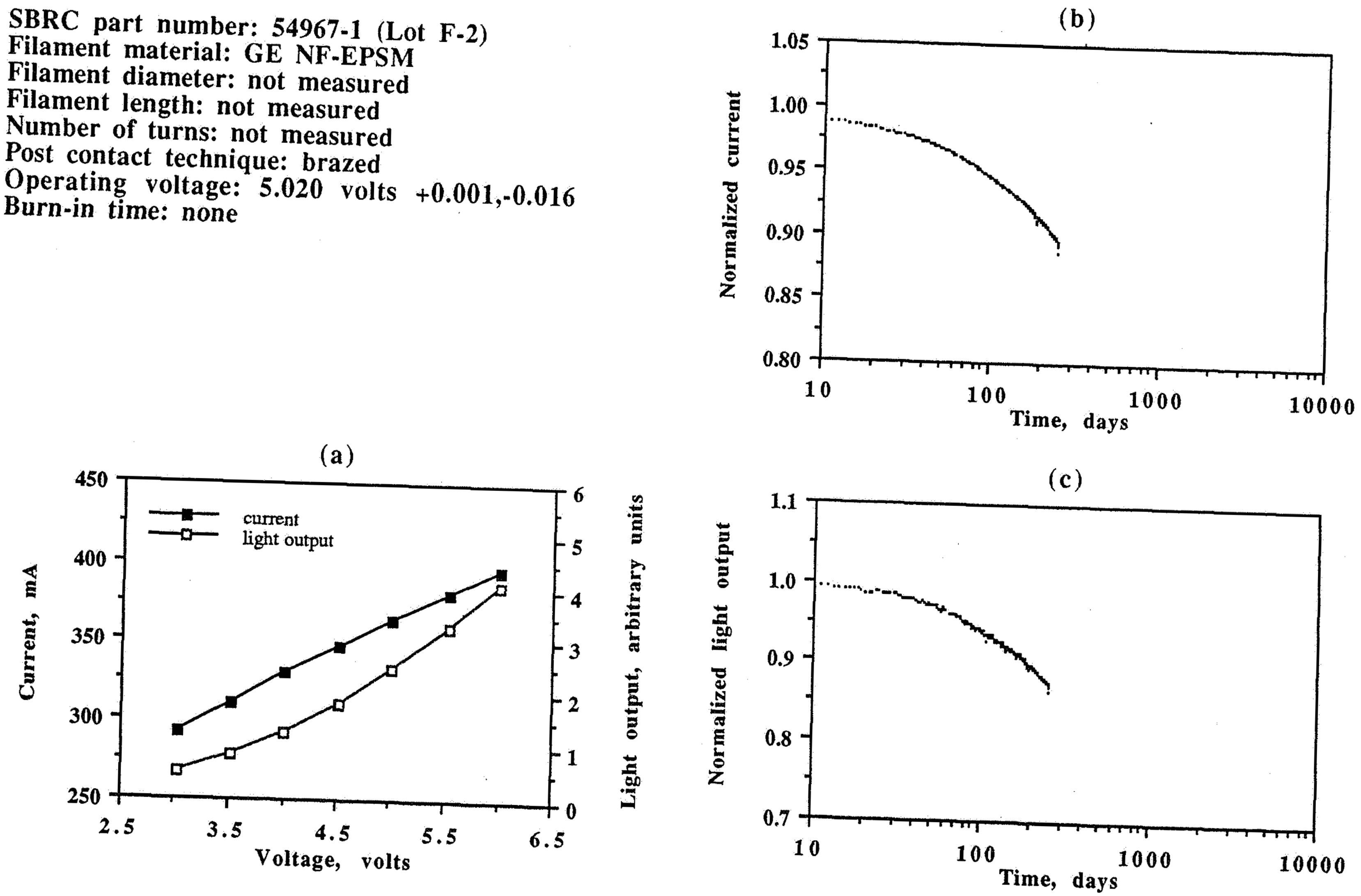


Figure A57. Lamp #17 of Experiment #4. This lamp burned-out after 257 days of operation. This lamp would have passed the burn in test (0.88% decrease in current). (a) Pre-life test characterization of the lamp. Lamp light output and current vs. voltage. (b) Lamp current vs. days of operation. (c) Lamp light output vs. days of operation.

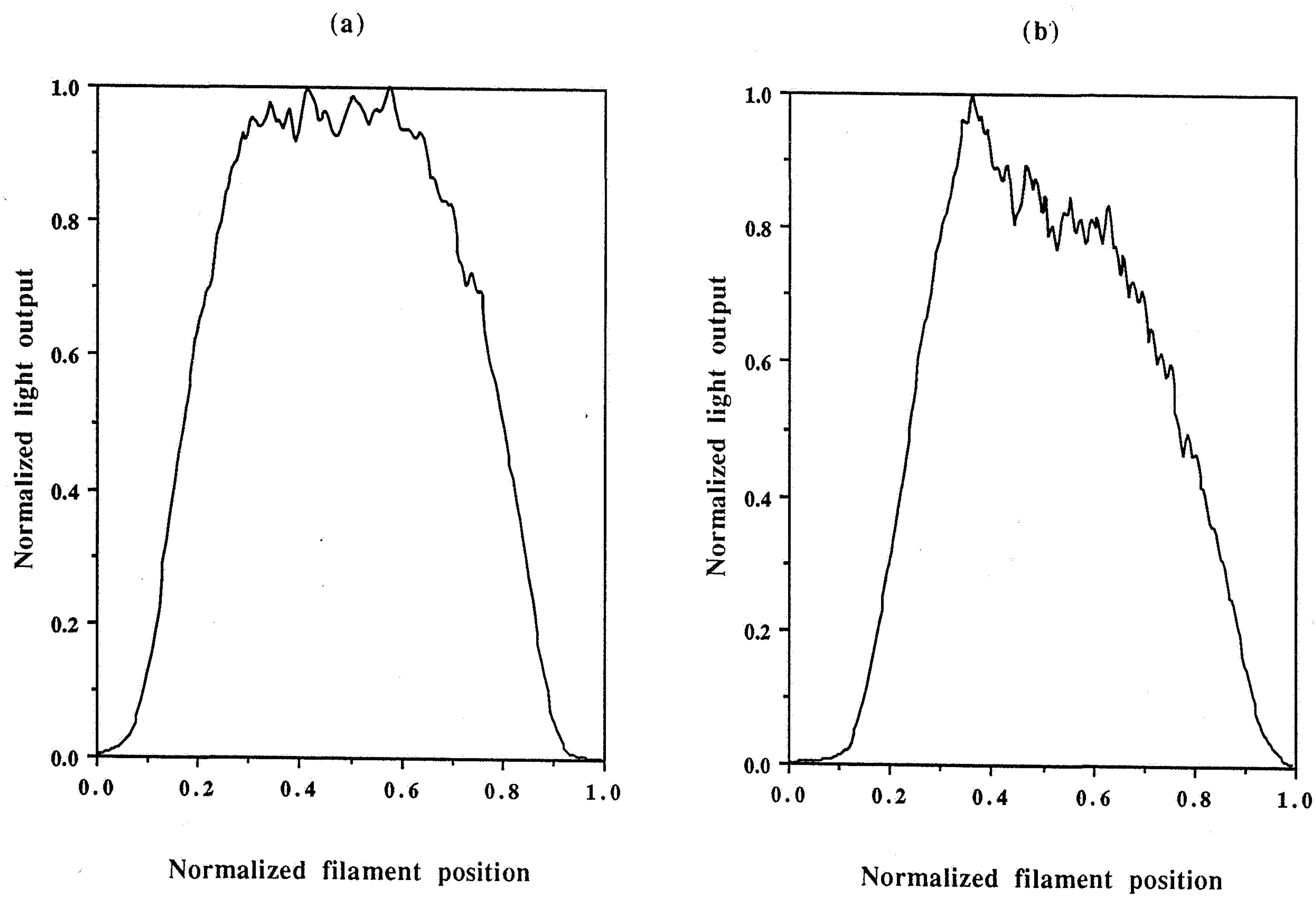


Figure A58. Lamp #17 of Experiment #4. These graphs show the light output from the lamp as a function of location along the filament. (a) 106 days of operation. (b) 211 days of operation.

SBRC part number: 54967-1 (Lot F-2)
Filament material: GE NF-EPSM
Filament diameter: 38.0 µm
Filament length: 3.400 mm
Number of turns: 55
Post contact technique: brazed
Operating voltage: 5.007 volts +0.004,-0.003
Burn-in time: none

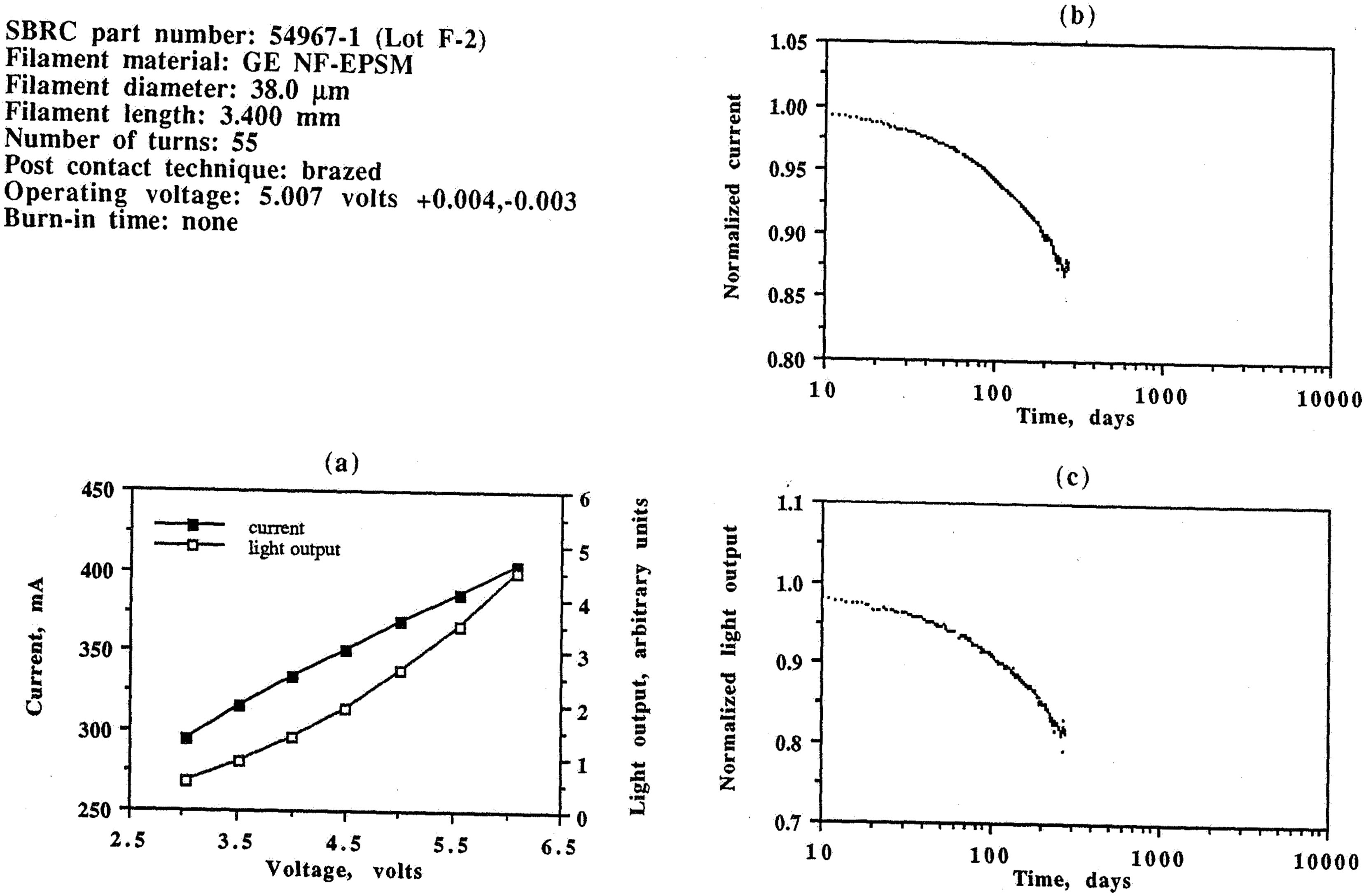


Figure A59. Lamp #18 of Experiment #4. This lamp burned-out after 277 days of operation. This lamp would have failed the burn in test (1.07% decrease in current). (a) Pre-life test characterization of the lamp. Lamp light output and current vs. voltage. (b) Lamp current vs. days of operation. (c) Lamp light output vs. days of operation.

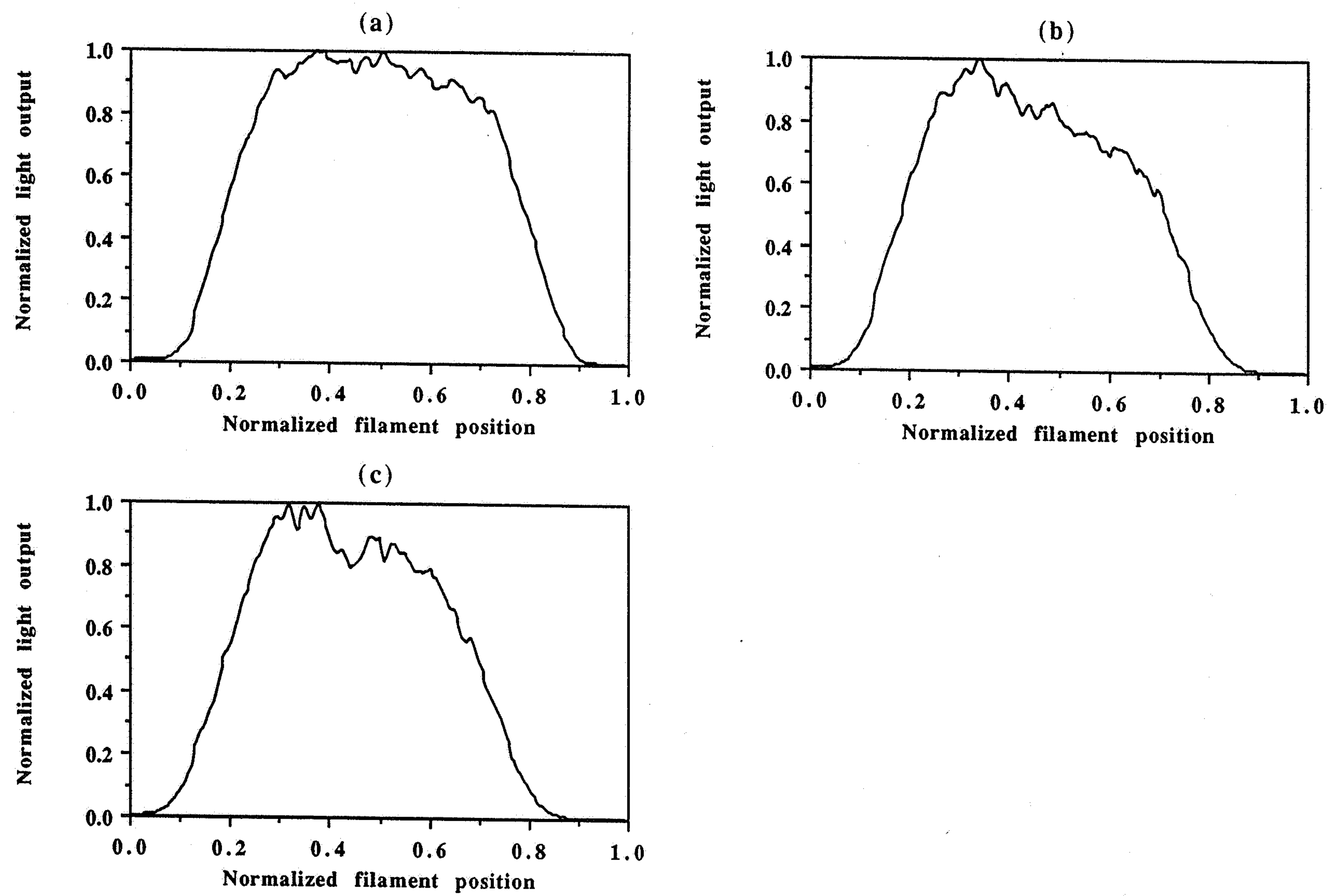
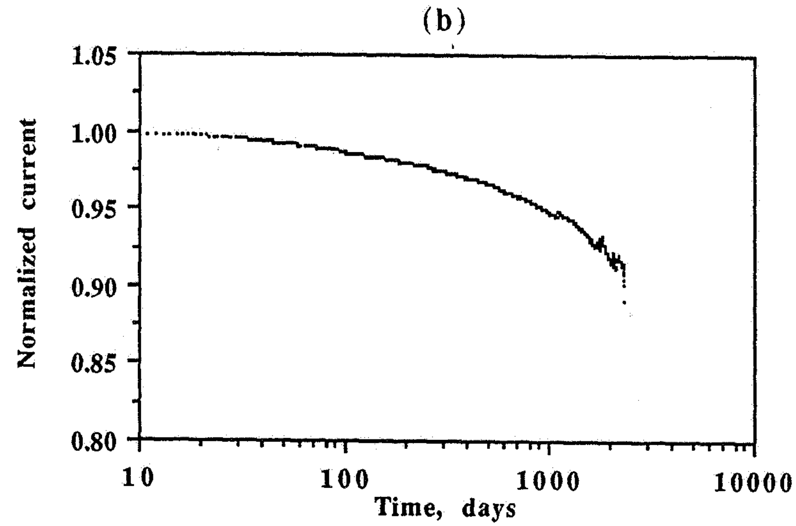
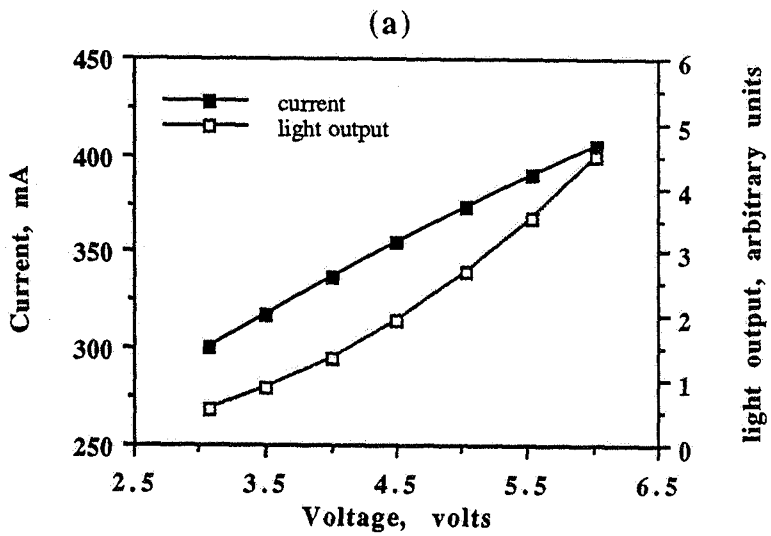


Figure A60. Lamp #18 of Experiment #4. These graphs show the light output from the lamp as a function of location along the filament. (a) 106 days of operation. (b) 211 days of operation. (c) 263 days of operation.

SBRC part number: 54967-4 (Lot F-2)
Filament material: Luma 821-42
Filament diameter: 37.0 μm
Filament length: 3.504 mm
Number of turns: 55
Post contact technique: brazed
Operating voltage: 3.550 volts +0.017,-0.016
Burn-in time: none





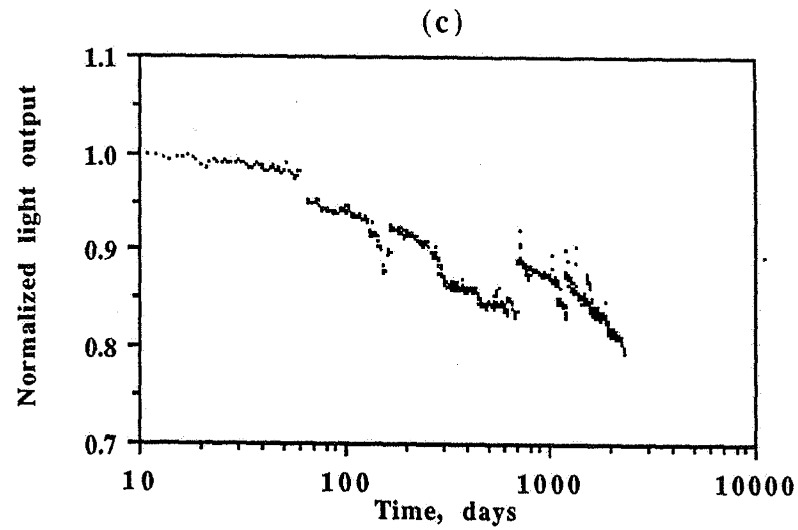


Figure A61. Lamp #19 of Experiment #4. This lamp burned-out after 2299 days of operation. (a) Pre-life test characterization of the lamp. Lamp light output and current vs. voltage. (b) Lamp current vs. days of operation. (c) Lamp light output vs. days of operation.

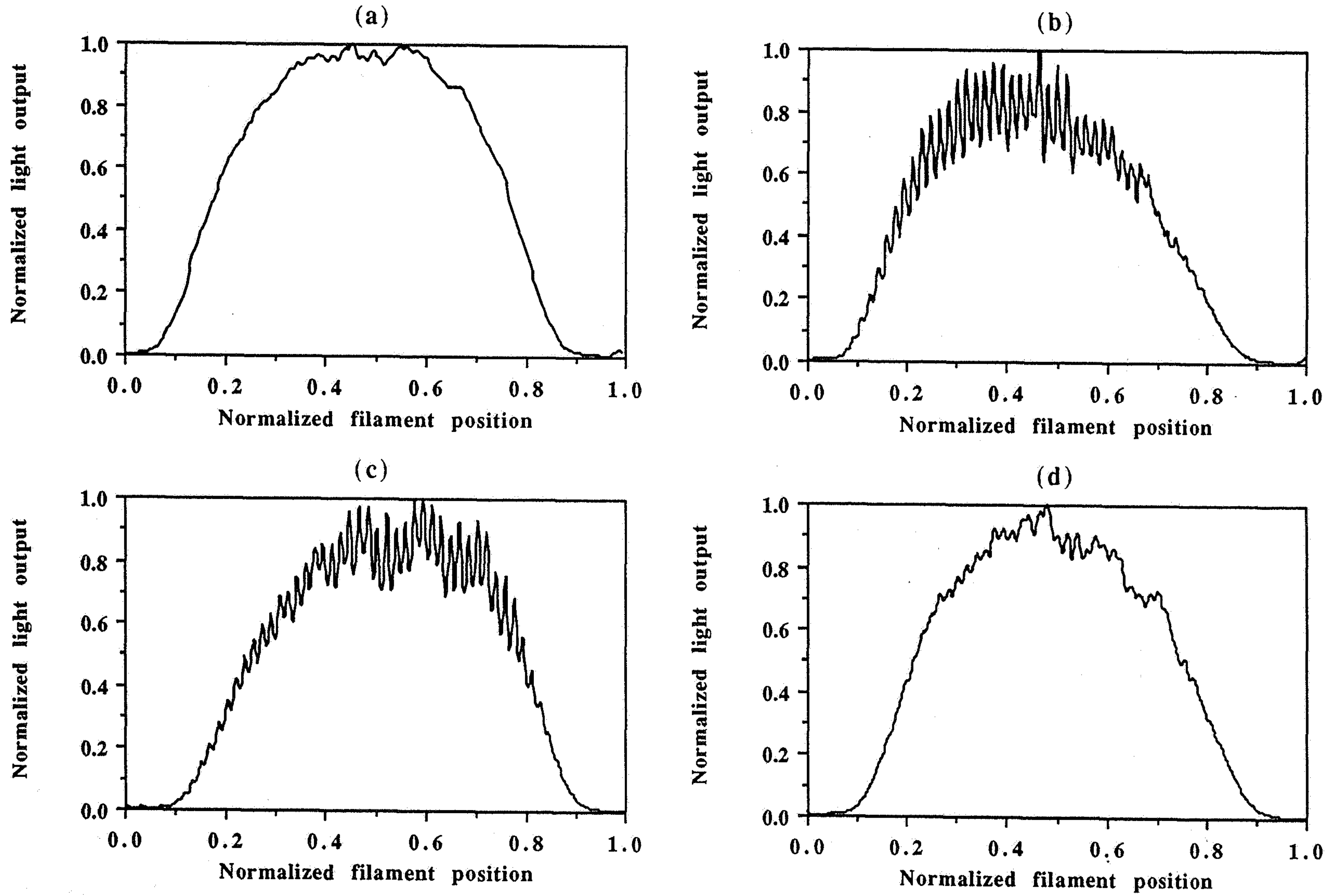
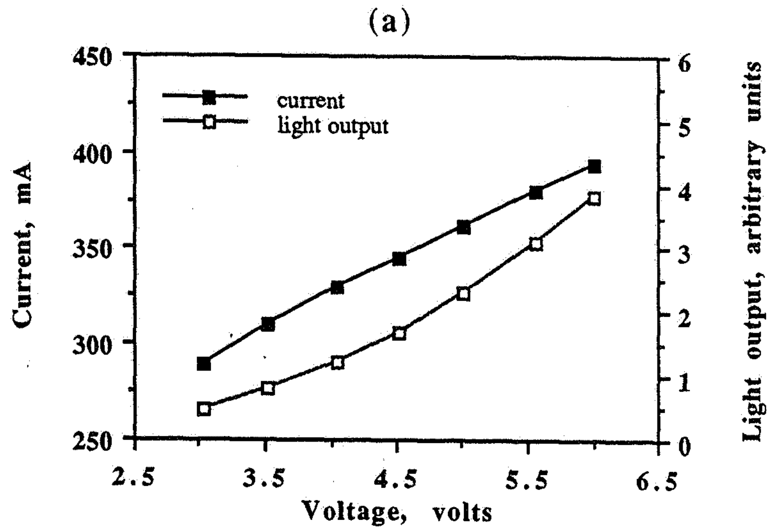
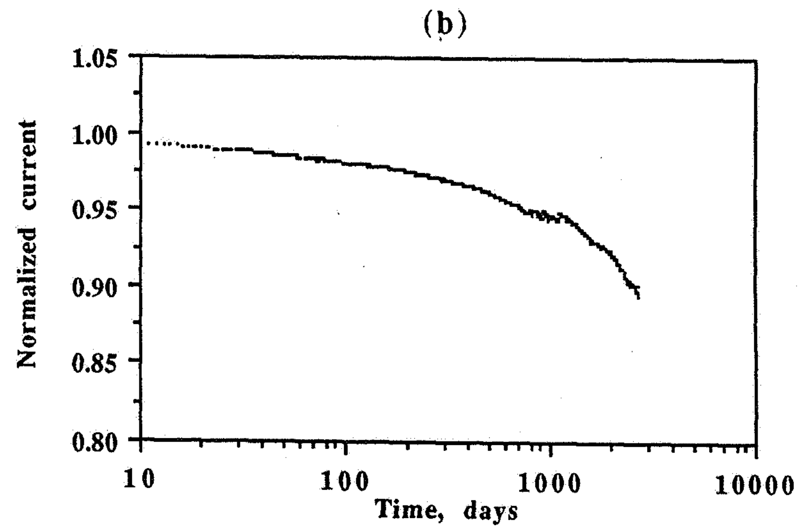


Figure A62. Lamp #19 of Experiment #4. These graphs show the light output from the lamp as a function of location along the filament. (a) 106 days of operation. (b) 590 days of operation. (c) 1023 days of operation. (d) 1476 days of operation.

C-2

SBRC part number: 54967-4 (Lot F-2)
Filament material: Luma 821-42
Filament diameter: not measured
Filament length: not measured
Number of turns: not measured
Post contact technique: brazed
Operating voltage: 3.557 volts +0.017,-0.016
Burn-in time: none





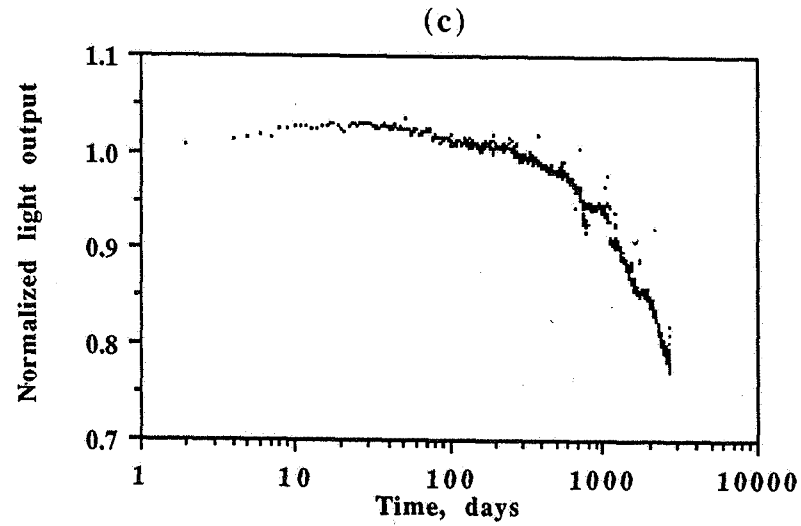


Figure A63. Lamp #20 of Experiment #4. This lamp was still operating after 2700 days. (a) Pre-life test characterization of the lamp. Lamp light output and current vs. voltage. (b) Lamp current vs. days of operation. (c) Lamp light output vs. days of operation.

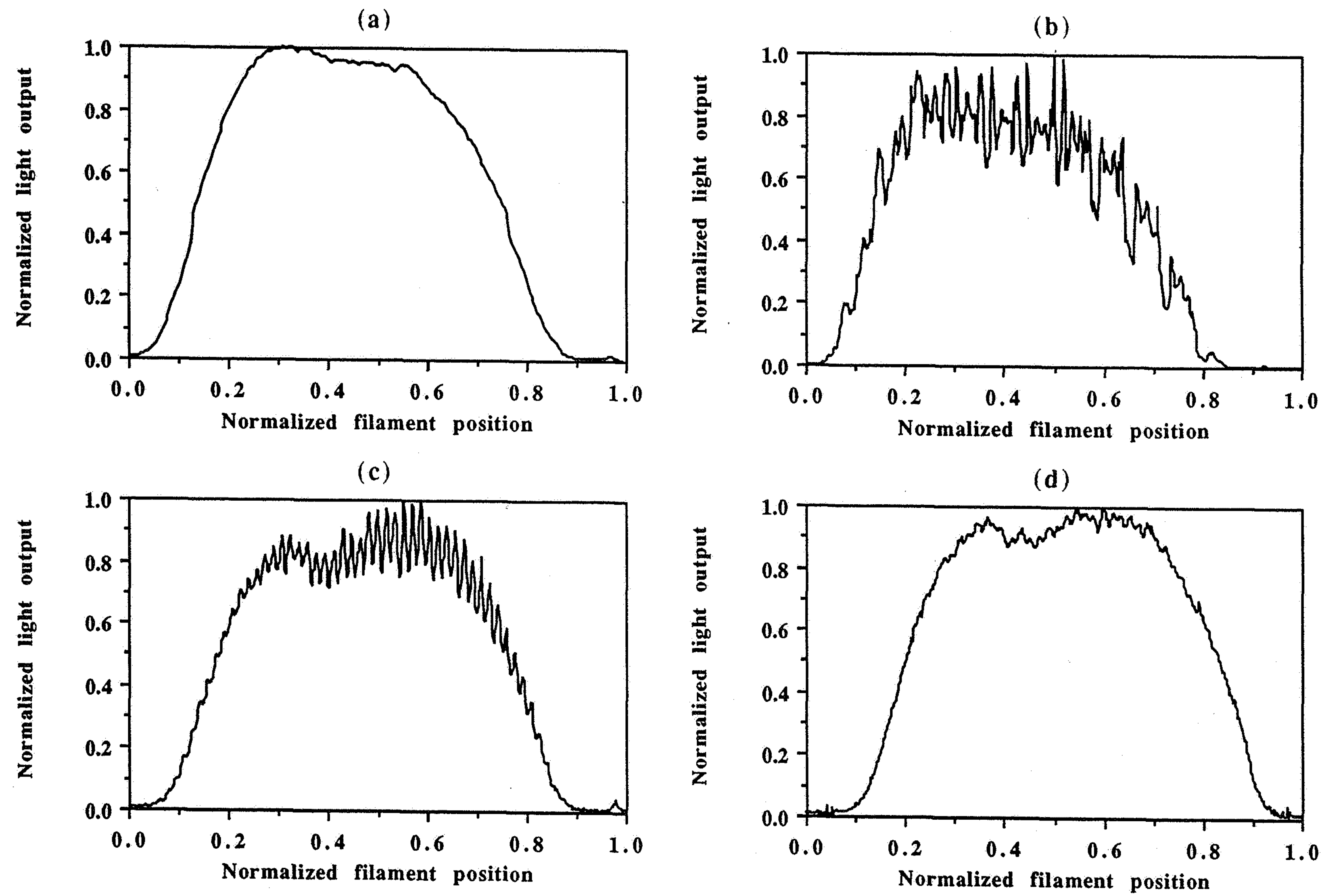


Figure A64. Lamp #20 of Experiment #4. These graphs show the light output from the lamp as a function of location along the filament. (a) 106 days of operation. (b) 590 days of operation. (c) 1023 days of operation. (d) 1476 days of operation.

SBRC part number: 54967-4 (Lot F-2)
Filament material: Luma 821-42
Filament diameter: 37.5 μm
Filament length: 3.309 mm
Number of turns: 54
Post contact technique: brazed
Operating voltage: 5.024 volts +0.002,-0.011
Burn-in time: none

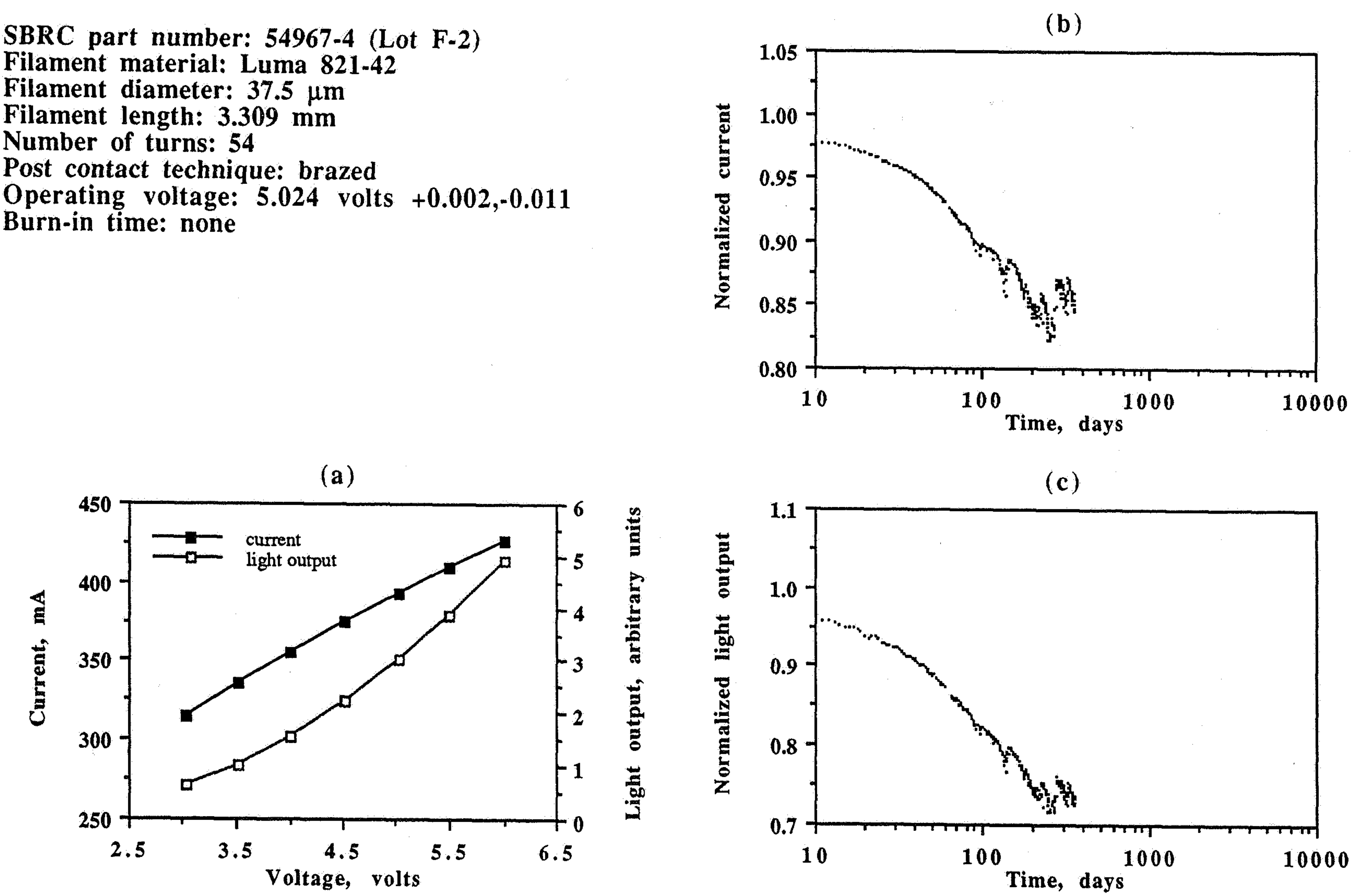


Figure A65. Lamp #25 of Experiment #4. This lamp burned-out after 352 days of operation. This lamp would have failed the burn in test (1.34% decrease in current). (a) Pre-life test characterization of the lamp. Lamp light output and current vs. voltage. (b) Lamp current vs. days of operation. (c) Lamp light output vs. days of operation.

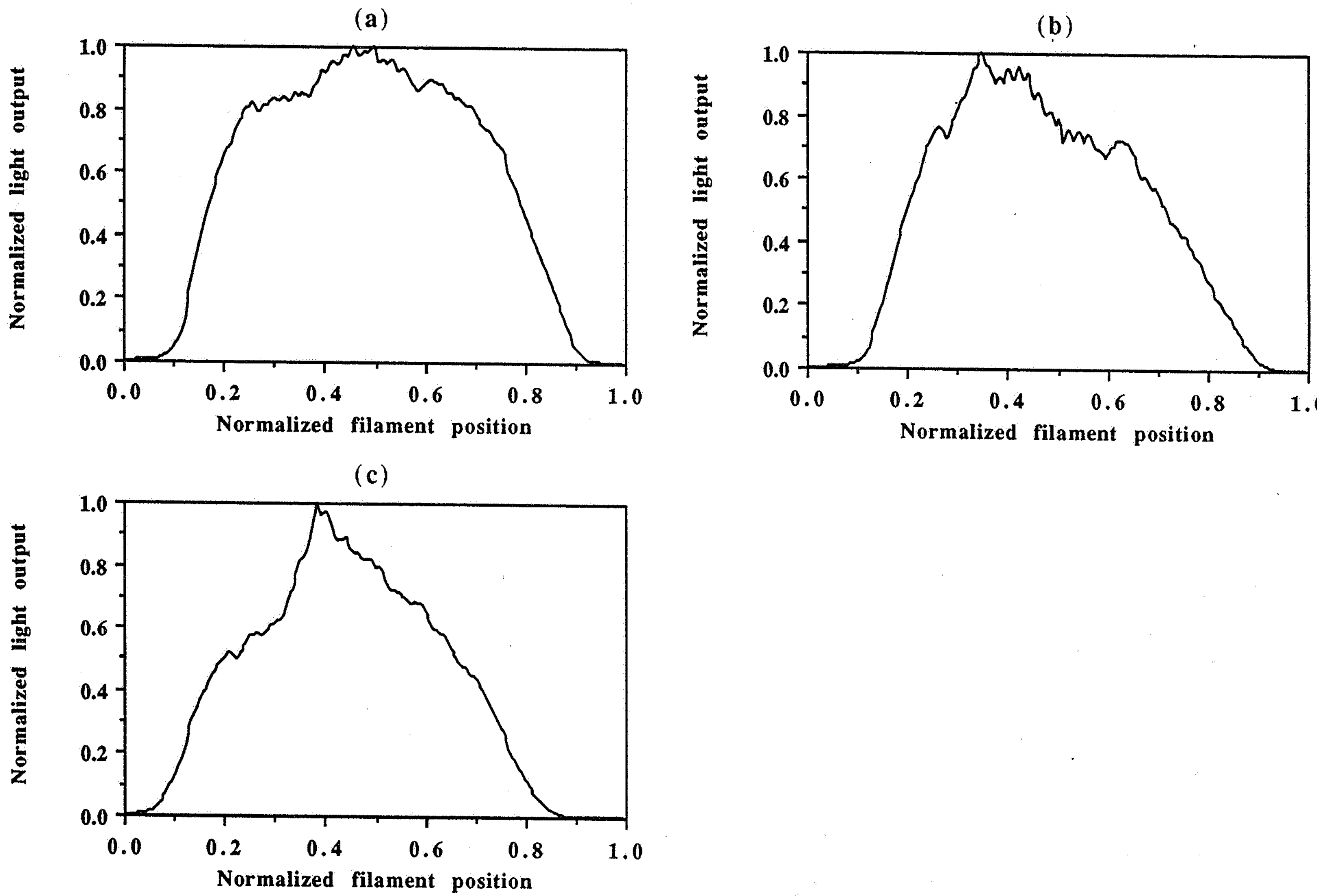
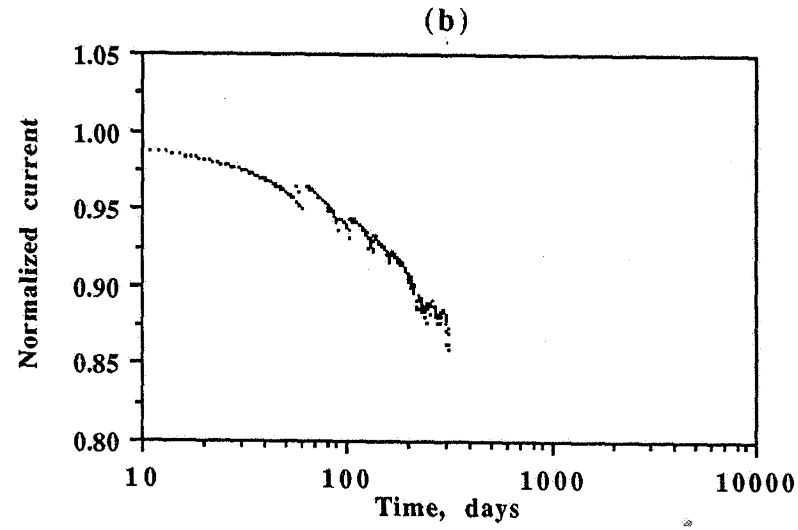
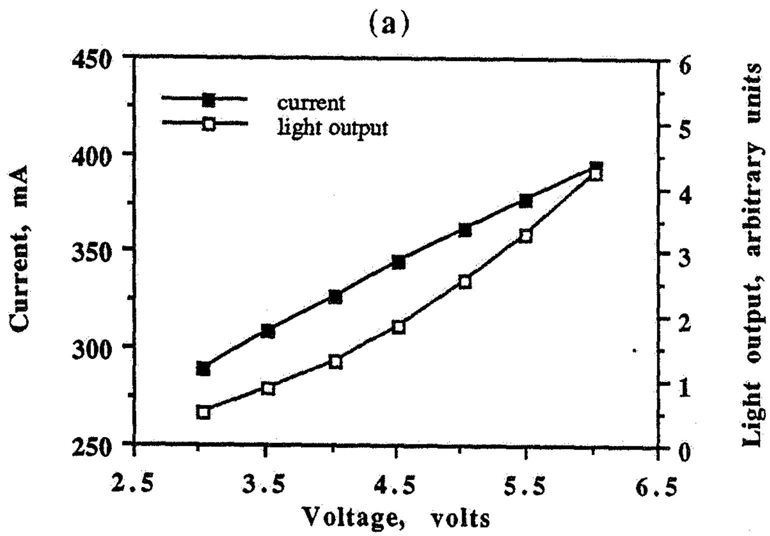


Figure A66. Lamp #25 of Experiment #4. These graphs show the light output from the lamp as a function of location along the filament. (a) 106 days of operation. (b) 211 days of operation. (c) 263 days of operation.

SBRC part number: 54967-4 (Lot F-2)
Filament material: Luma 821-42
Filament diameter: 36.9 μm
Filament length: 3.443 mm
Number of turns: 55
Post contact technique: brazed
Operating voltage: 5.002 volts +0.008,-0.005
Burn-in time: none





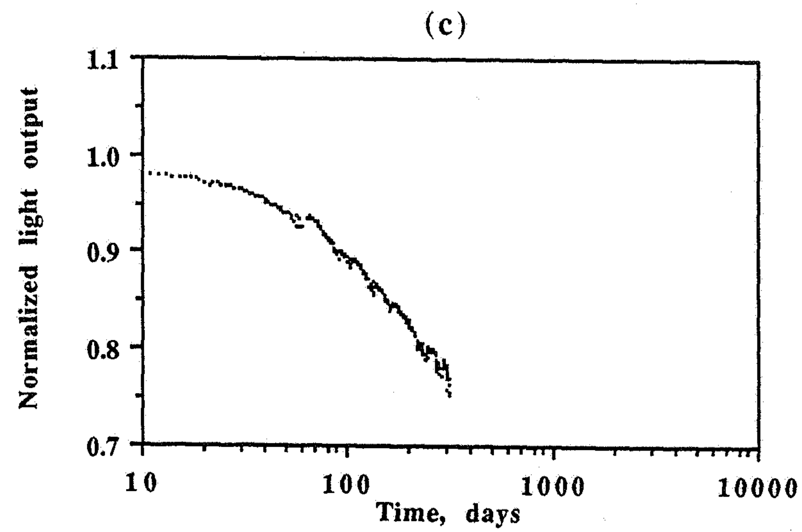


Figure A67. Lamp #26 of Experiment #4. This lamp burned-out after 311 days of operation. This lamp would have failed the burn in test (1.02% decrease in current). (a) Pre-life test characterization of the lamp. Lamp light output and current vs. voltage. (b) Lamp current vs. days of operation. (c) Lamp light output vs. days of operation.

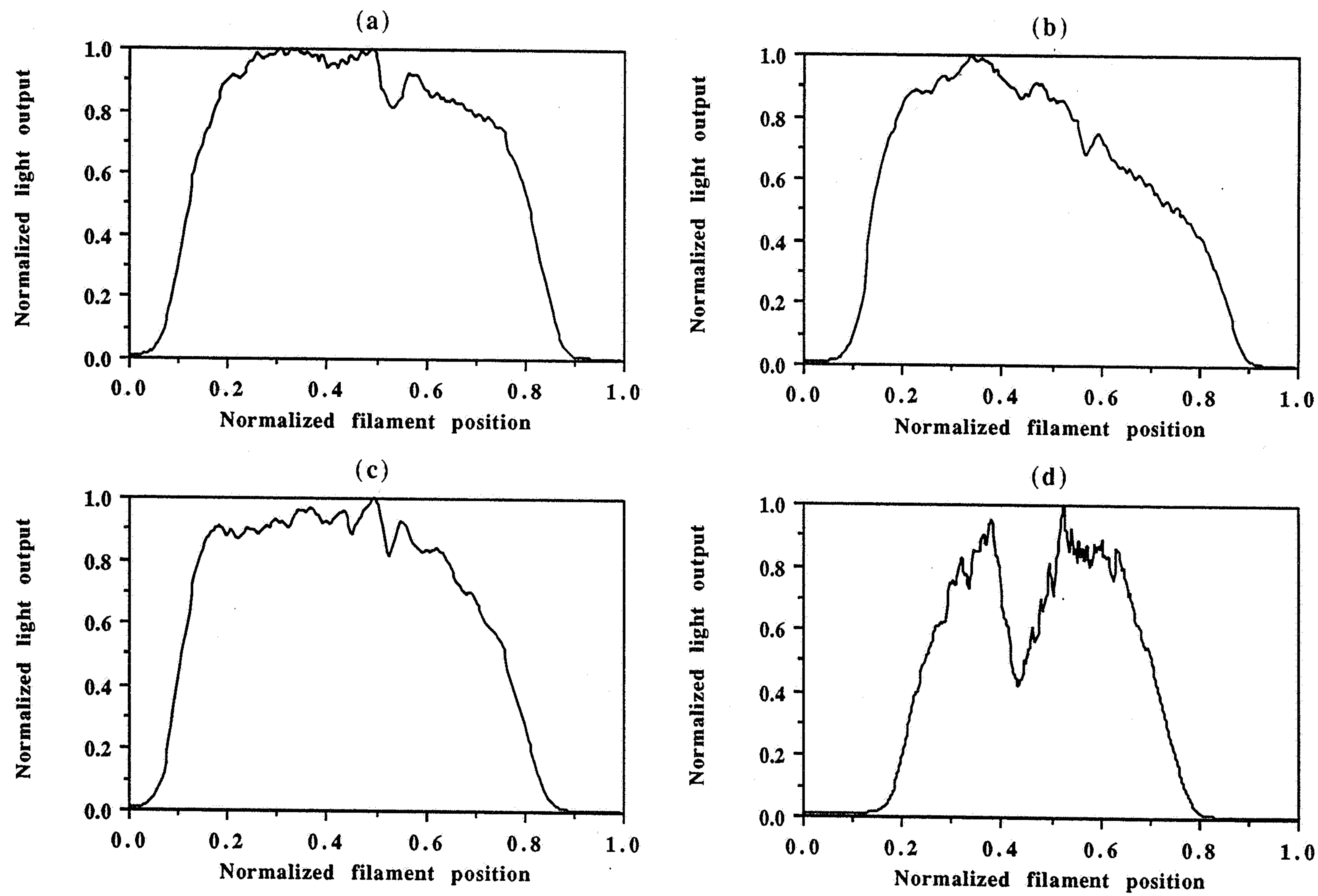


Figure A68. Lamp #26 of Experiment #4. These graphs show the light output from the lamp as a function of location along the filament. (a) 106 days of operation. (b) 211 days of operation. (c) 263 days of operation. (d) 321 days of operation.

SBRC part number: 54967-3 (Lot F-1)
Filament material: Luma 861-42
Filament diameter: 37.5 µm
Filament length: 3.140 mm
Number of turns: 53
Post contact technique: brazed
Operating voltage: 3.553 volts +0.003,-0.011
Burn-in time: none

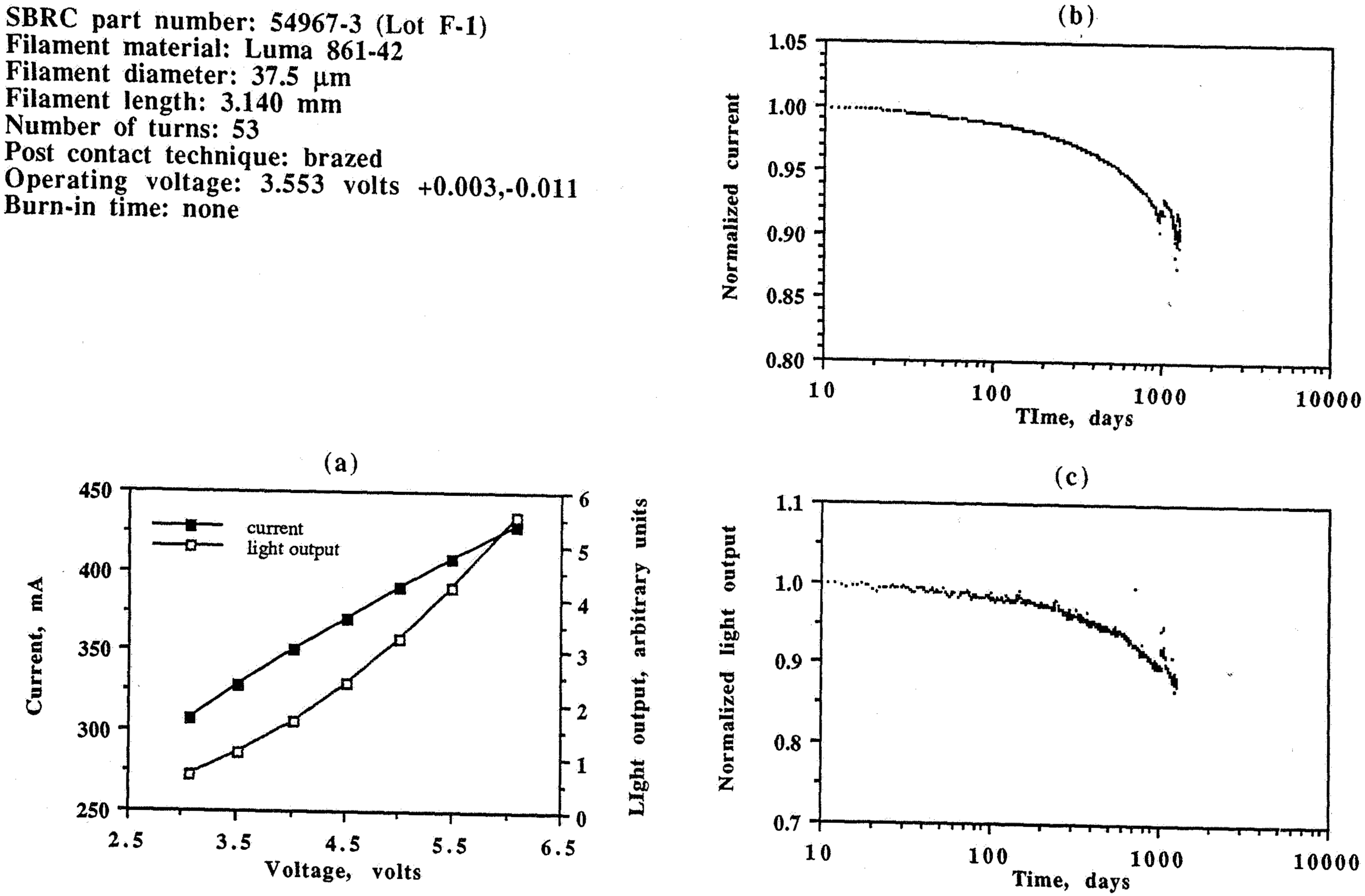


Figure A69. Lamp #28 of Experiment #4. This lamp burned-out after 1275 days of operation. (a) Pre-life test characterization of the lamp. Lamp light output and current vs. voltage. (b) Lamp current vs. days of operation. (c) Lamp light output vs. days of operation.

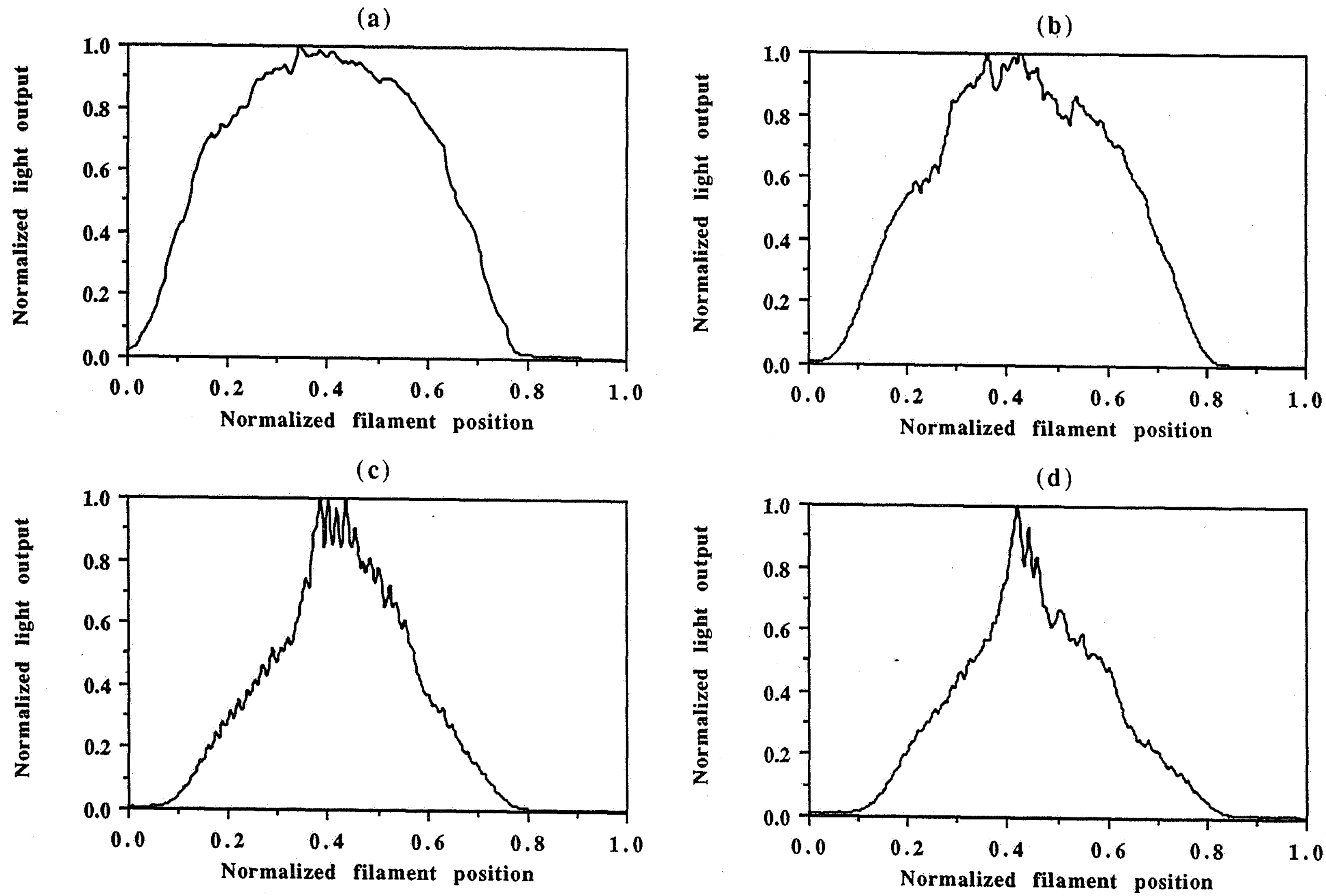


Figure A70. Lamp #28 of Experiment #4. These graphs show the light output from the lamp as a function of location along the filament. (a) 106 days of operation. (b) 443 days of operation. (c) 952 days of operation. (d) 1209 days of operation.

SBRC part number: 54967-3 (Lot F-1)
Filament material: Luma 861-42
Filament diameter: not measured
Filament length: not measured
Number of turns: not measured
Post contact technique: brazed
Operating voltage: 3.544 volts +0.005,-0.008
Burn-in time: none

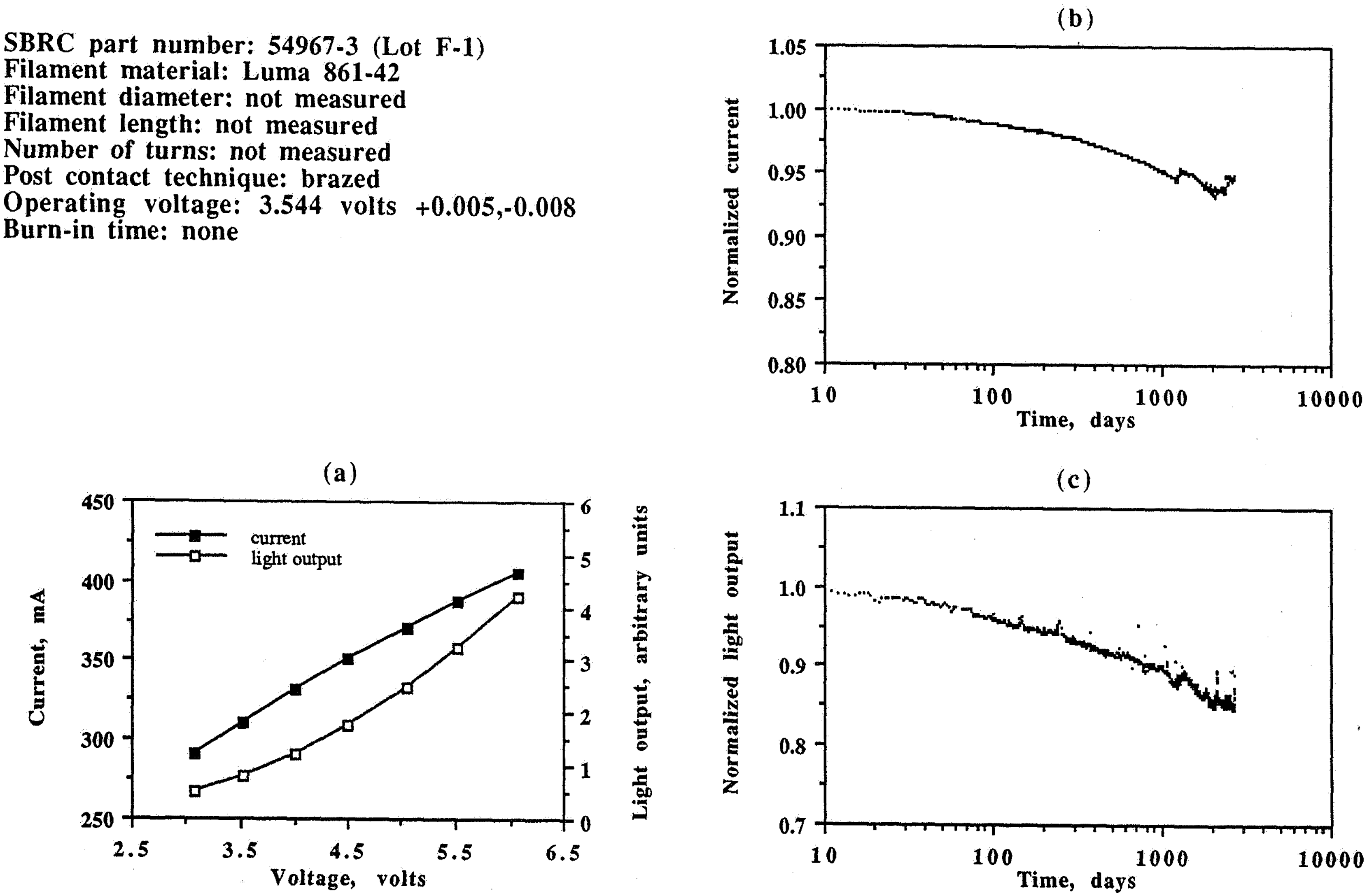


Figure A71. Lamp #29 of Experiment #4. This lamp was still operating after 2700 days. (a) Pre-life test characterization of the lamp. Lamp light output and current vs. voltage. (b) Lamp current vs. days of operation. (c) Lamp light output vs. days of operation.

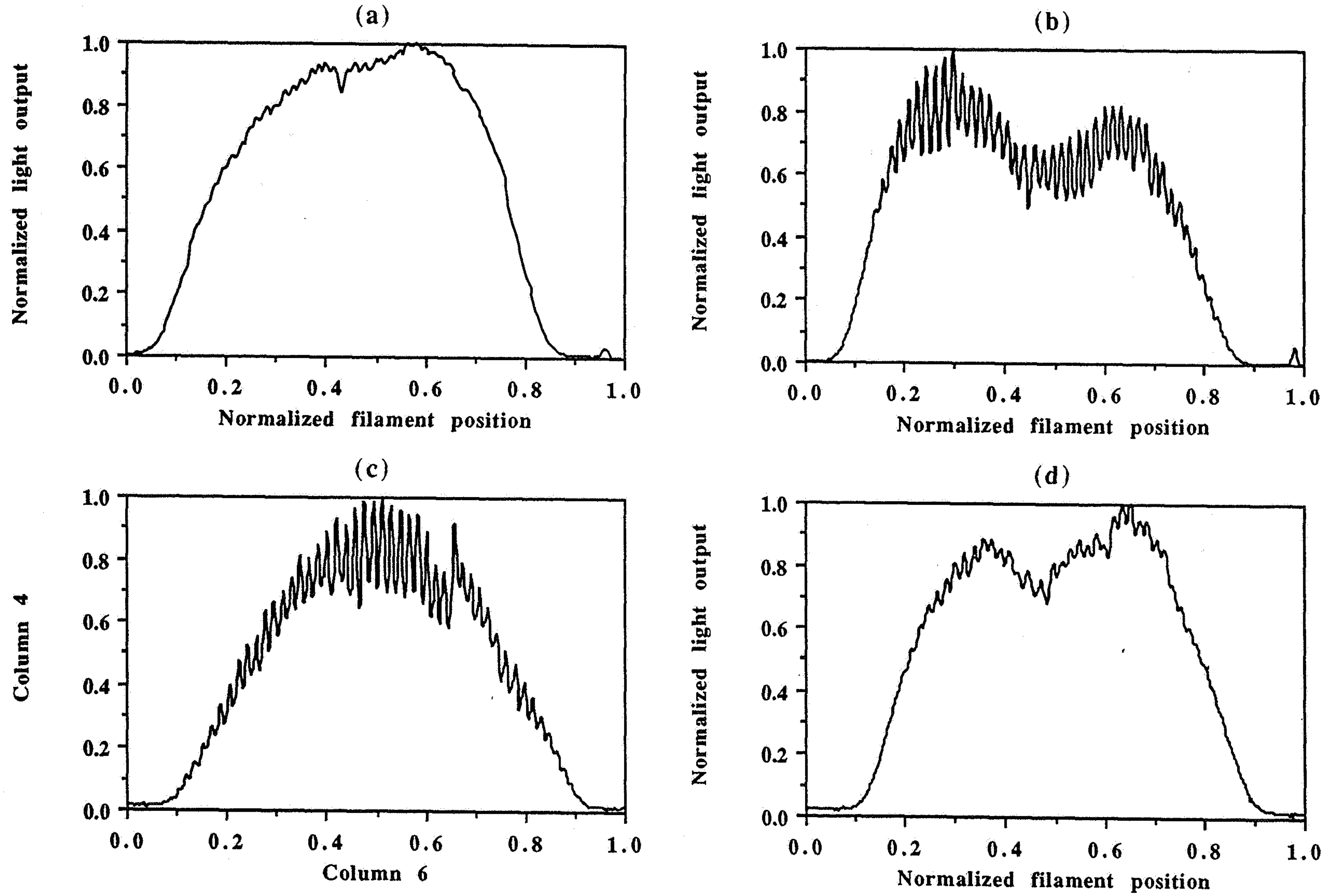
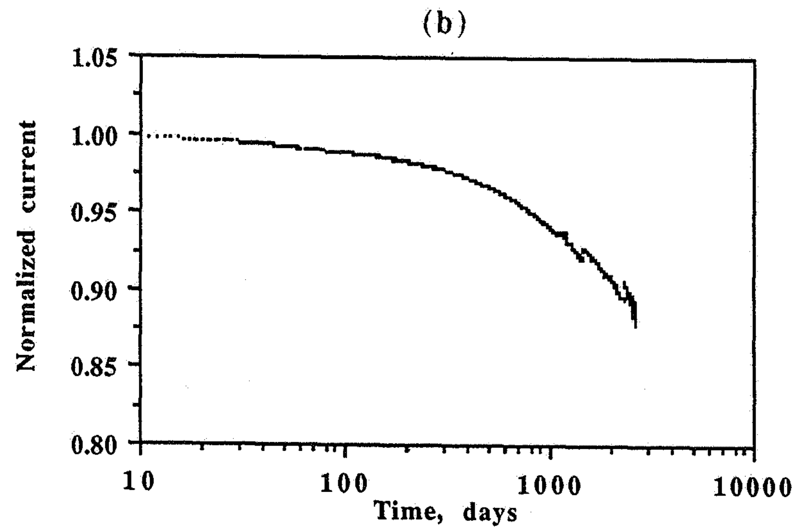
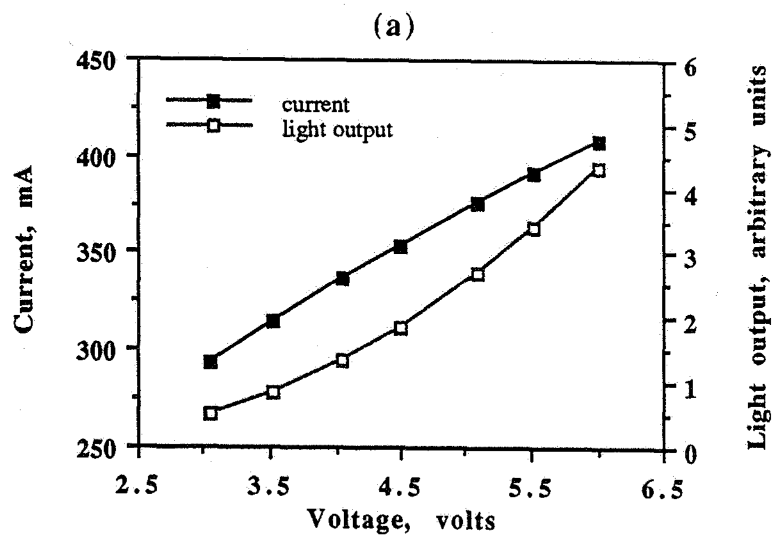


Figure A72. Lamp #29 of Experiment #4. These graphs show the light output from the lamp as a function of location along the filament. (a) 106 days of operation. (b) 590 days of operation. (c) 1023 days of operation. (d) 1476 days of operation.

SBRC part number: 54967-3 (Lot F-1)
Filament material: Luma 861-42
Filament diameter: 38.2 μm
Filament length: 3.540 mm
Number of turns: 57
Post contact technique: brazed
Operating voltage: 3.549 volts +0.006,-0.009
Burn-in time: none





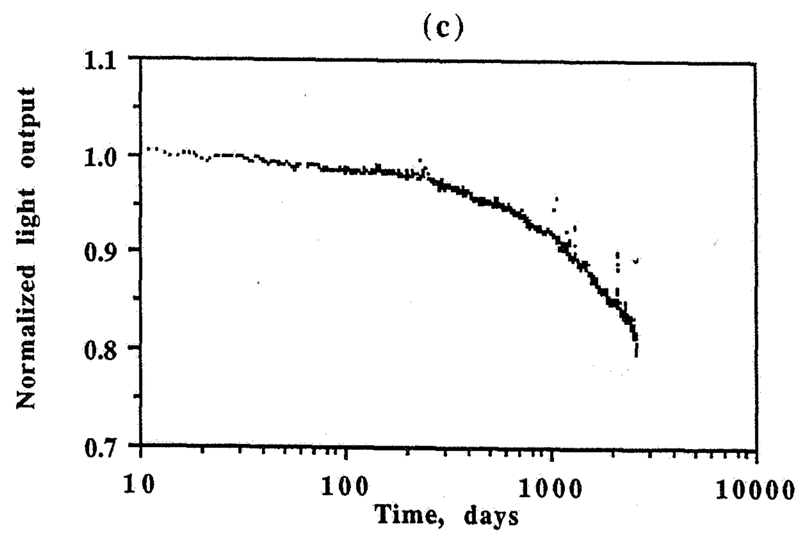


Figure A73. Lamp #30 of Experiment #4. This lamp burned-out after 2588 days of operation. (a) Pre-life test characterization of the lamp. Lamp light output and current vs. voltage. (b) Lamp current vs. days of operation. (c) Lamp light output vs. days of operation.

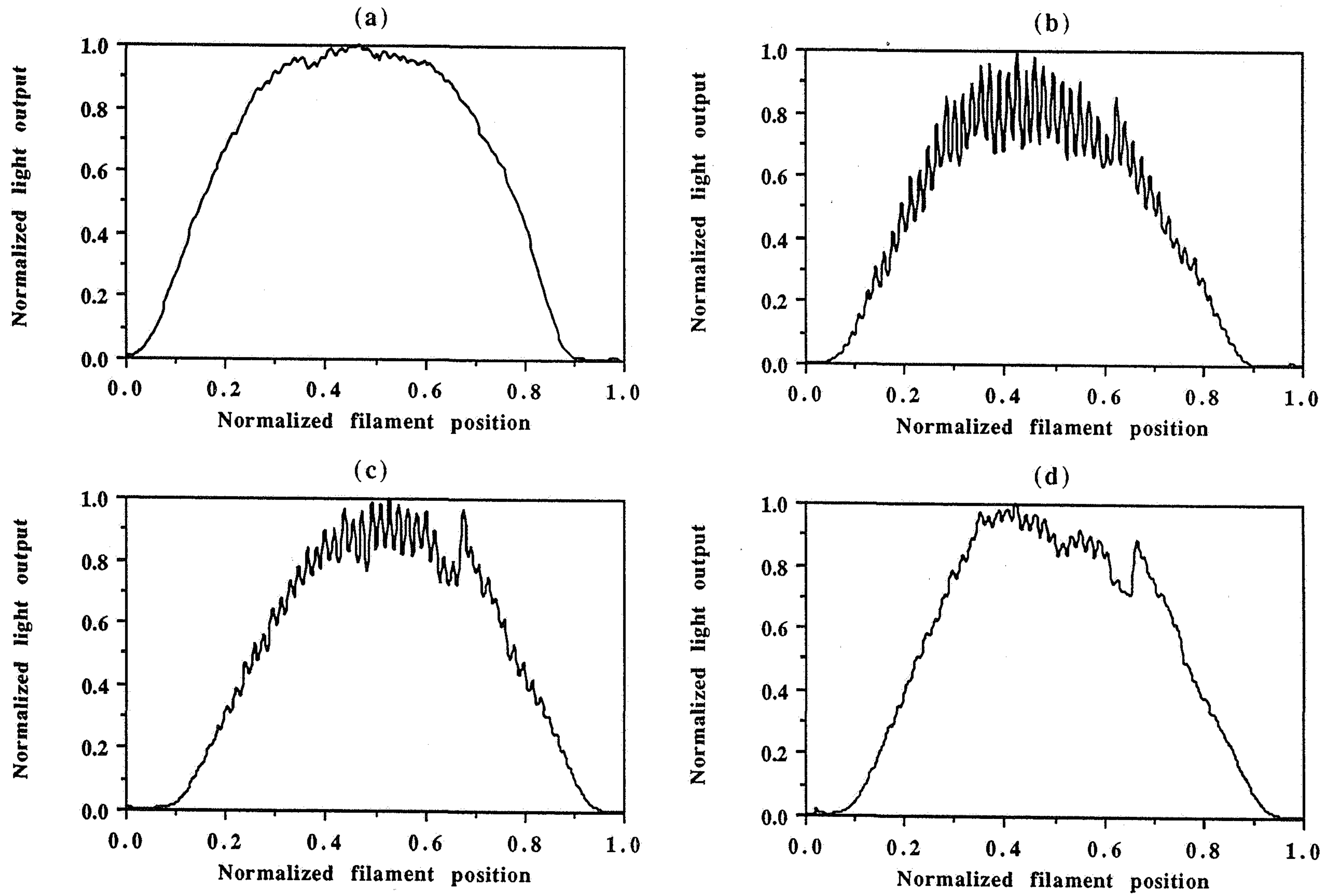
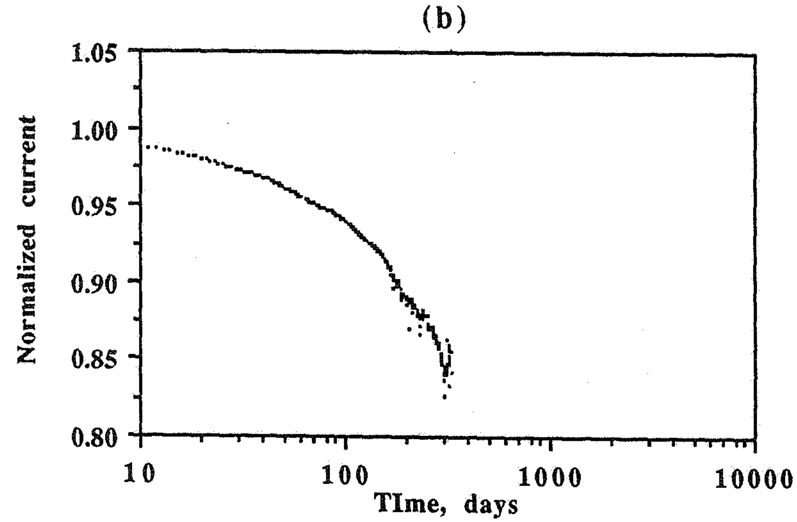
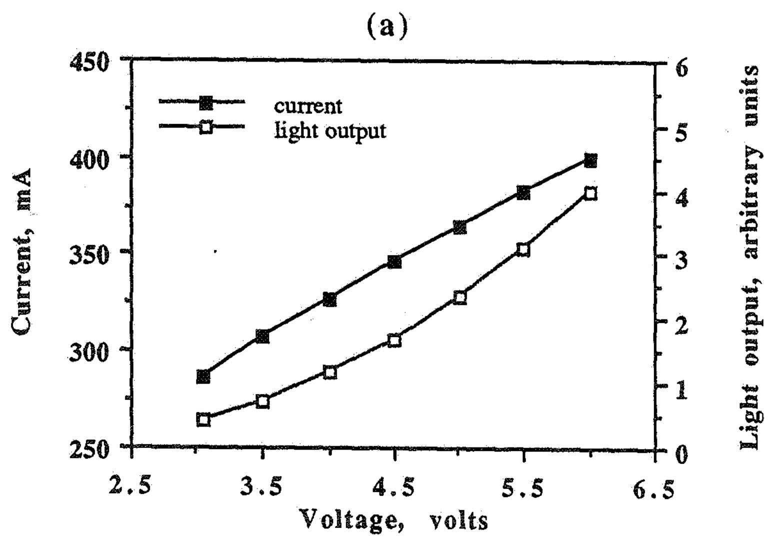


Figure A74. Lamp #30 of Experiment #4. These graphs show the light output from the lamp as a function of location along the filament. (a) 106 days of operation. (b) 590 days of operation. (c) 1023 days of operation. (d) 1476 days of operation.

SBRC part number: 54967-3 (Lot F-1)
Filament material: Luma 861-42
Filament diameter: 39.5 μm
Filament length: 3.613 mm
Number of turns: 58
Post contact technique: brazed
Operating voltage: 5.003 volts +0.002,-0.005
Burn-in time: none





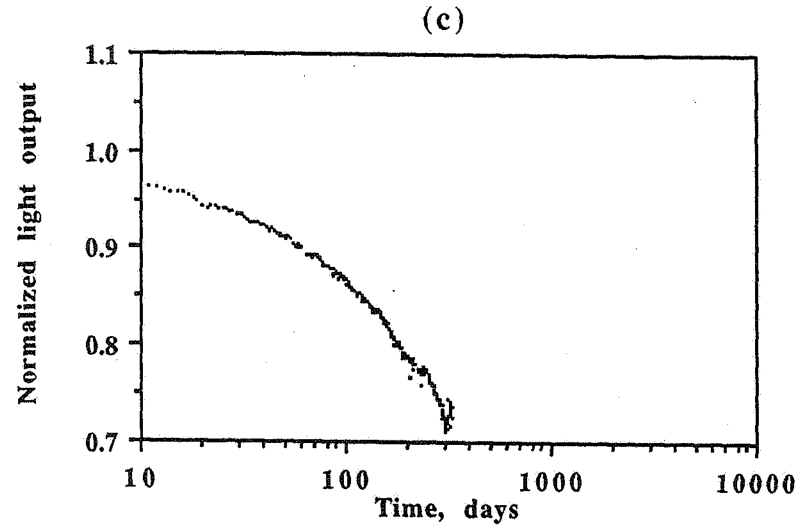


Figure A75. Lamp #34 of Experiment #4. This lamp burned-out after 328 days of operation. This lamp would have failed the burn in test (1.17% decrease in current). (a) Pre-life test characterization of the lamp. Lamp light output and current vs. voltage. (b) Lamp current vs. days of operation. (c) Lamp light output vs. days of operation.

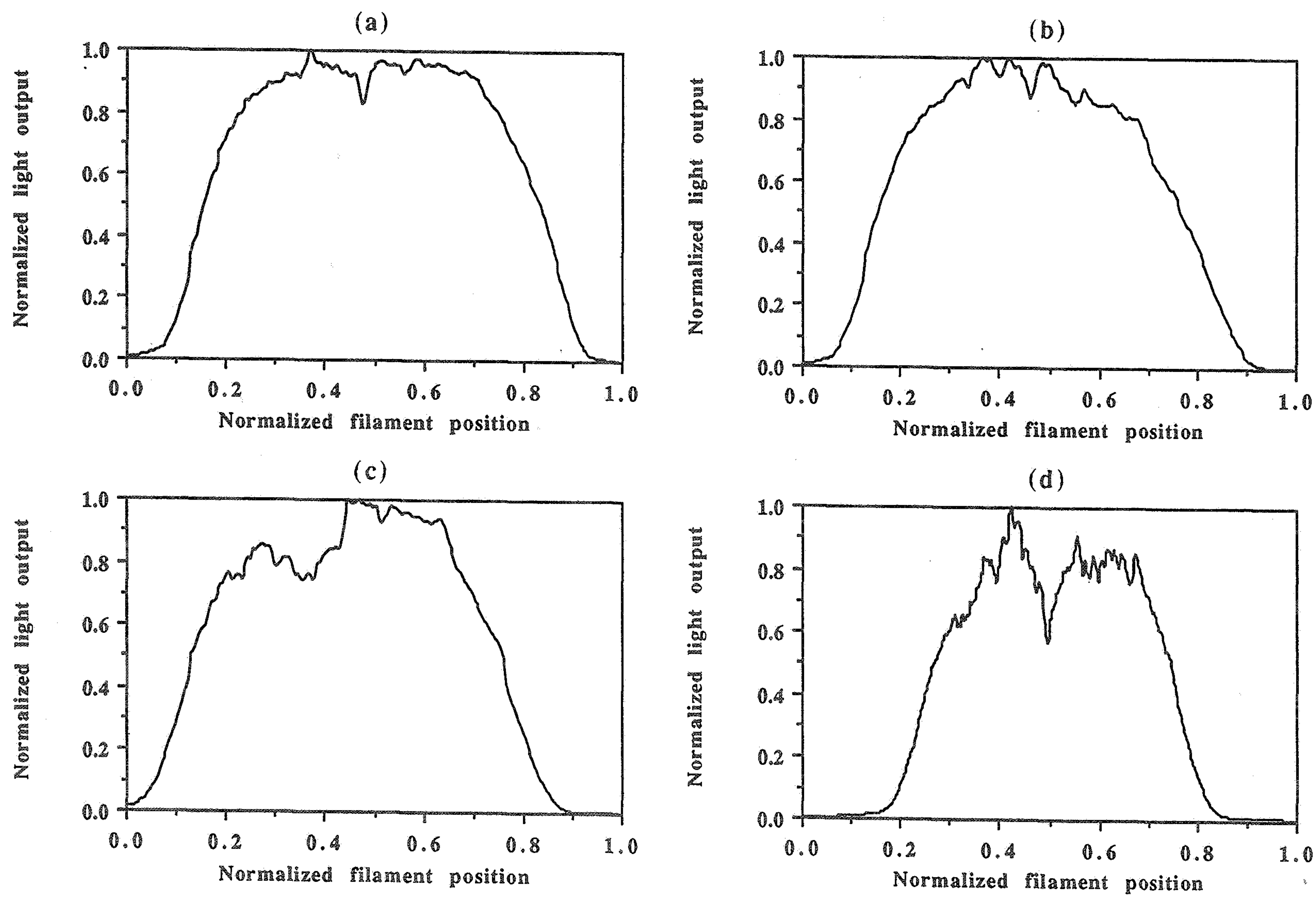


Figure A76. Lamp #34 of Experiment #4. These graphs show the light output from the lamp as a function of location along the filament. (a) 106 days of operation. (b) 211 days of operation. (c) 263 days of operation. (d) 321 days of operation.

SBRC part number: 54967-3 (Lot F-1)
Filament material: Luma 861-42
Filament diameter: 37.8 µm
Filament length: 3.565 mm
Number of turns: 57
Post contact technique: brazed
Operating voltage: 5.008 volts +0.003,-0.011
Burn-in time: none

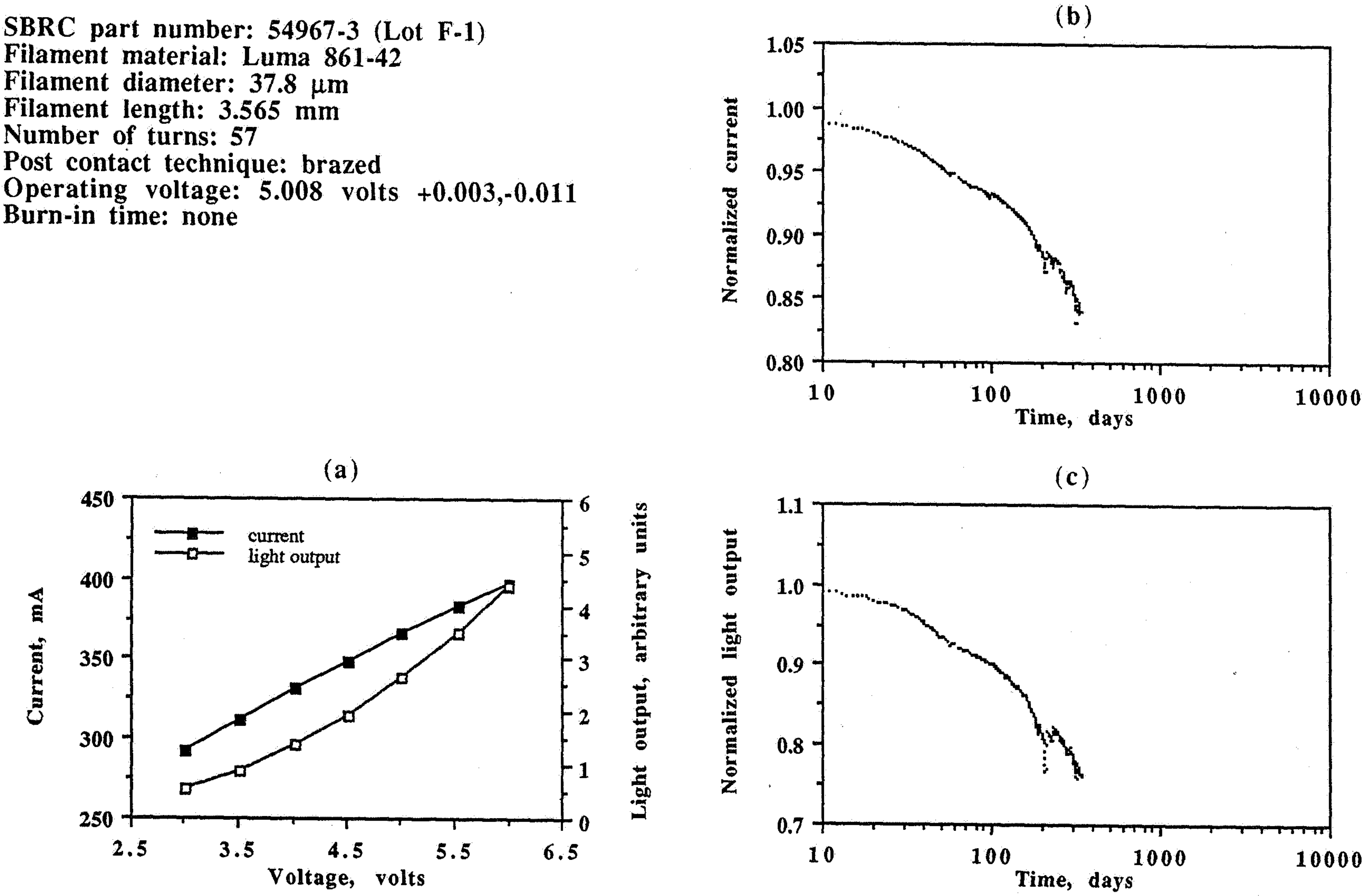


Figure A77. Lamp #35 of Experiment #4. This lamp burned-out after 339 days of operation. This lamp would have failed the burn in test (1.18% decrease in current). (a) Pre-life test characterization of the lamp. Lamp light output and current vs. voltage. (b) Lamp current vs. days of operation. (c) Lamp light output vs. days of operation.

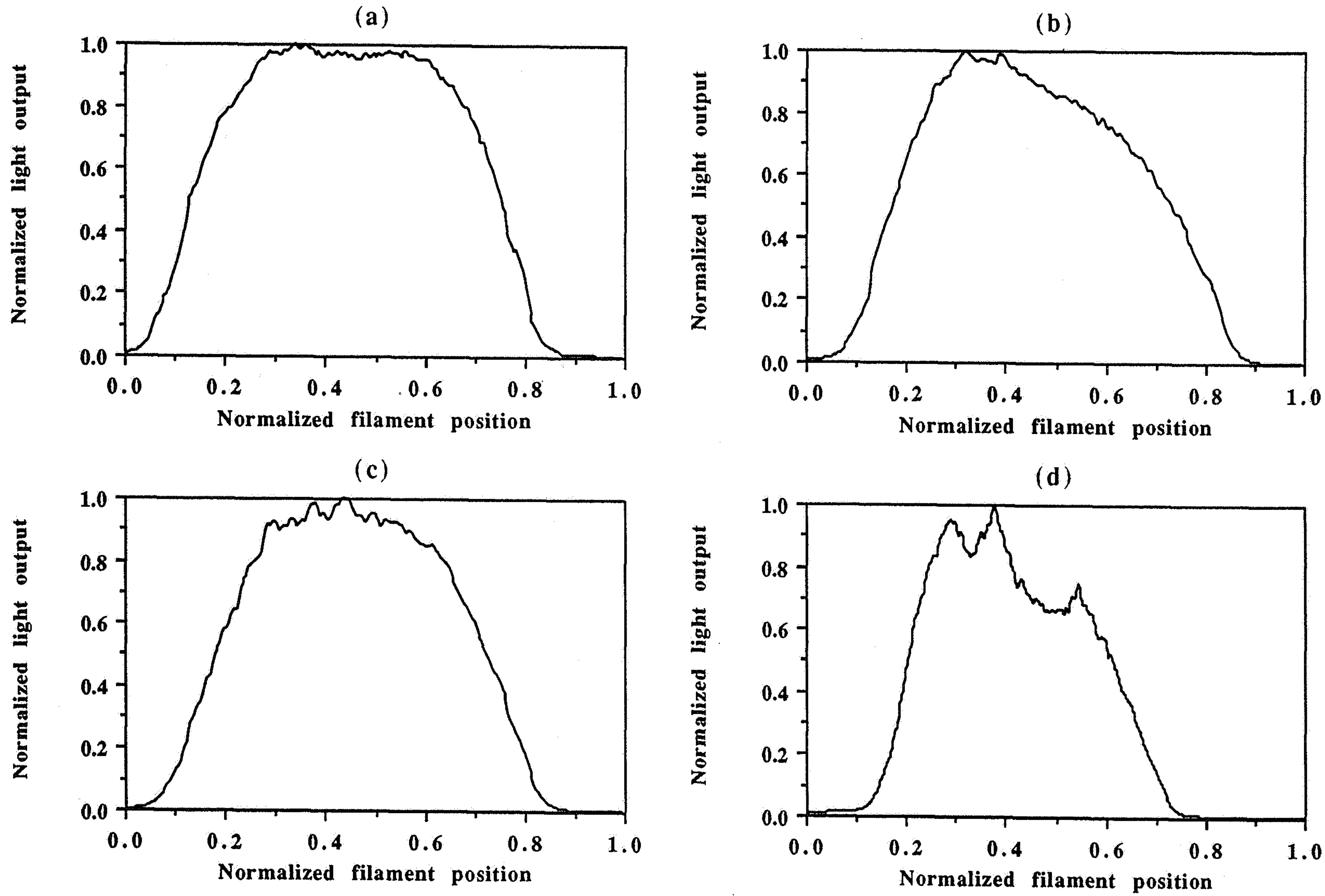
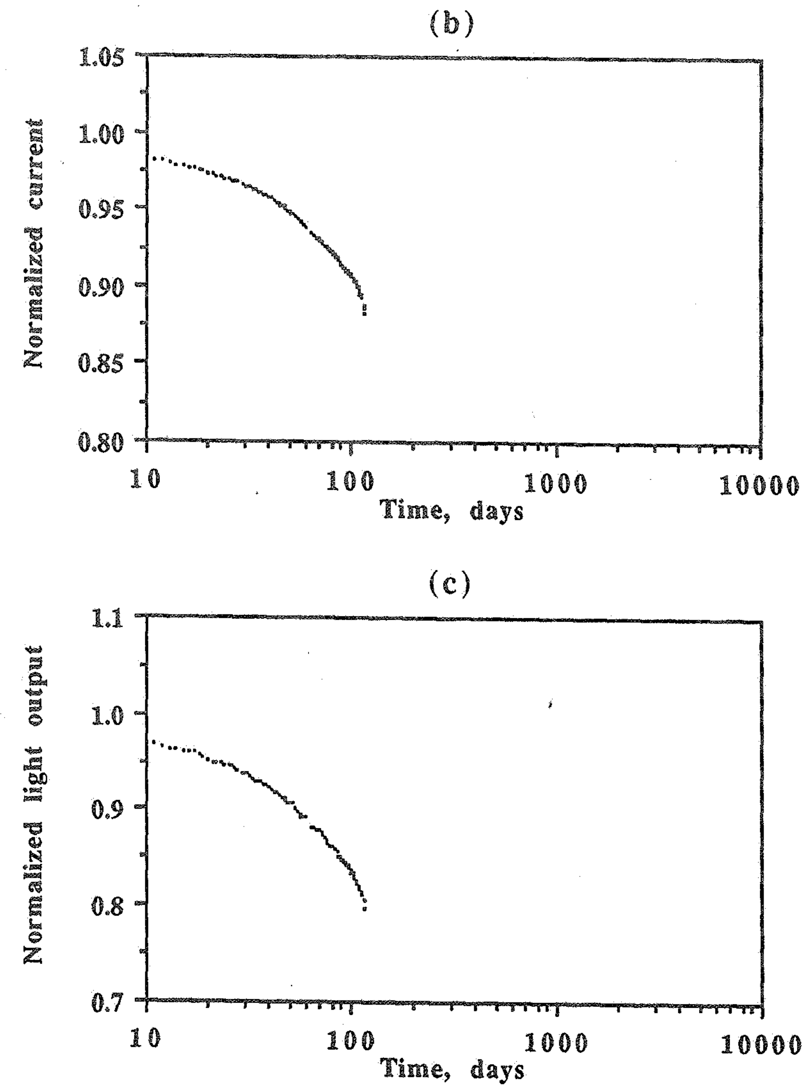


Figure A78. Lamp #35 of Experiment #4. These graphs show the light output from the lamp as a function of location along the filament. (a) 106 days of operation. (b) 211 days of operation. (c) 263 days of operation. (d) 321 days of operation.

SBRC part number: 54967-3 (Lot F-1)
Filament material: Luma 861-42
Filament diameter: 37.7 µm
Filament length: 3.179 mm
Number of turns: 51
Post contact technique: brazed
Operating voltage: 5.009 volts +0.002,-0.005
Burn-in time: none



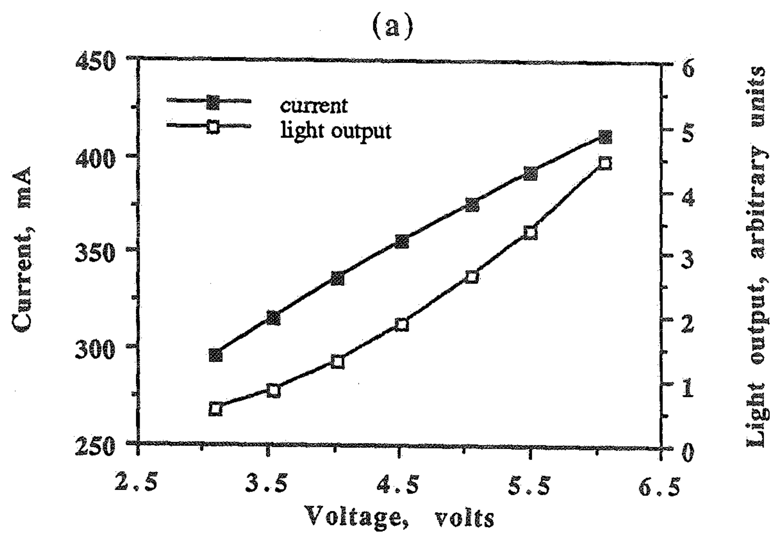


Figure A79. Lamp #36 of Experiment #4. This lamp burned-out after 118 days of operation. This lamp would have failed the burn in test (1.28% decrease in current). (a) Pre-life test characterization of the lamp. Lamp light output and current vs. voltage. (b) Lamp current vs. days of operation. (c) Lamp light output vs. days of operation.

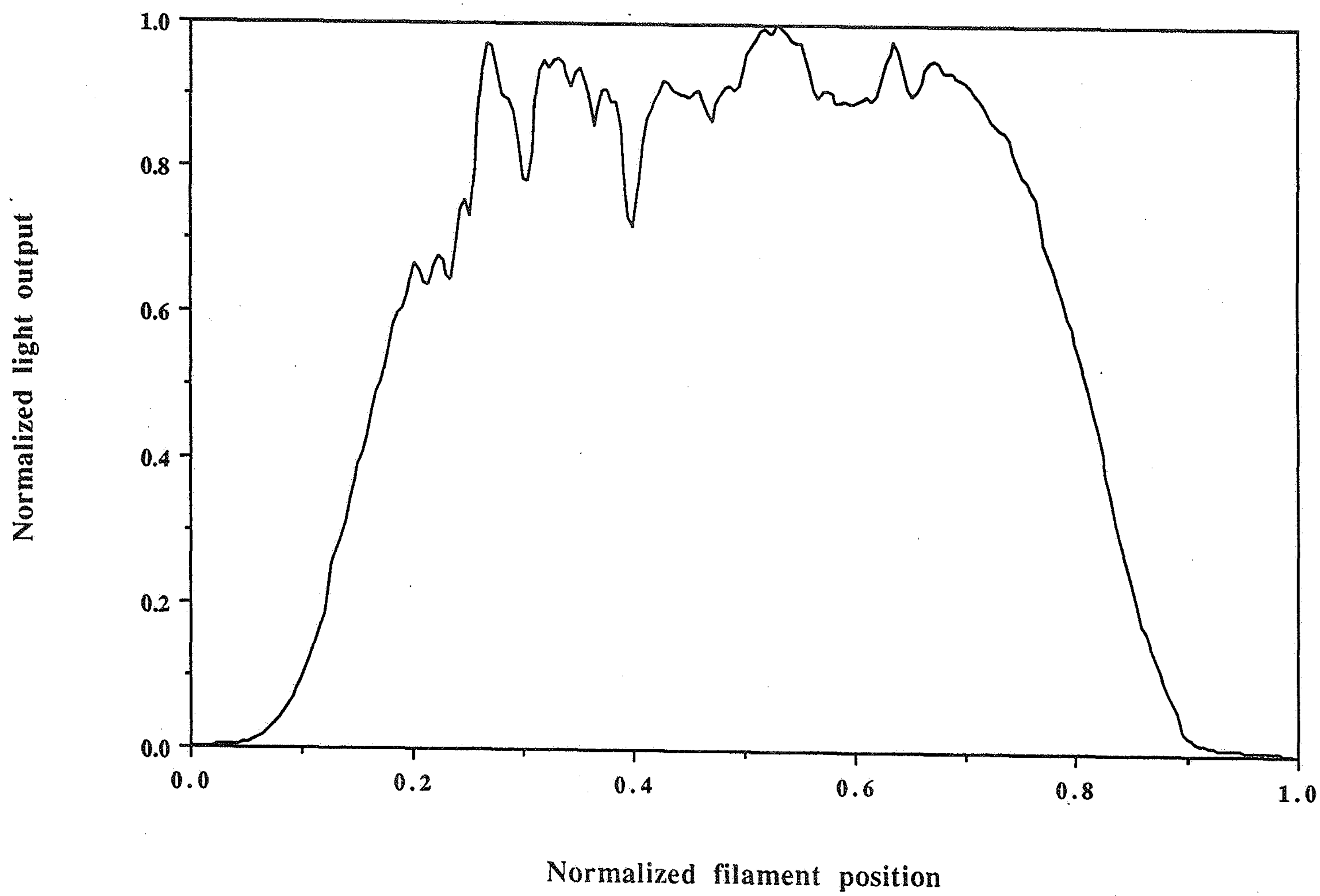


Figure A80. Lamp #36 of Experiment #4. This graph shows the light output from the lamp as a function of location along the filament after 106 days of operation.

SBRC part number: none
Filament material: GE-218W
Filament diameter: 37.5 µm
Filament length: 3.850 mm
Number of turns: not measured
Post contact technique: welded
Operating voltage: 4.685 volts +0.007,-0.014
Burn-in time: none

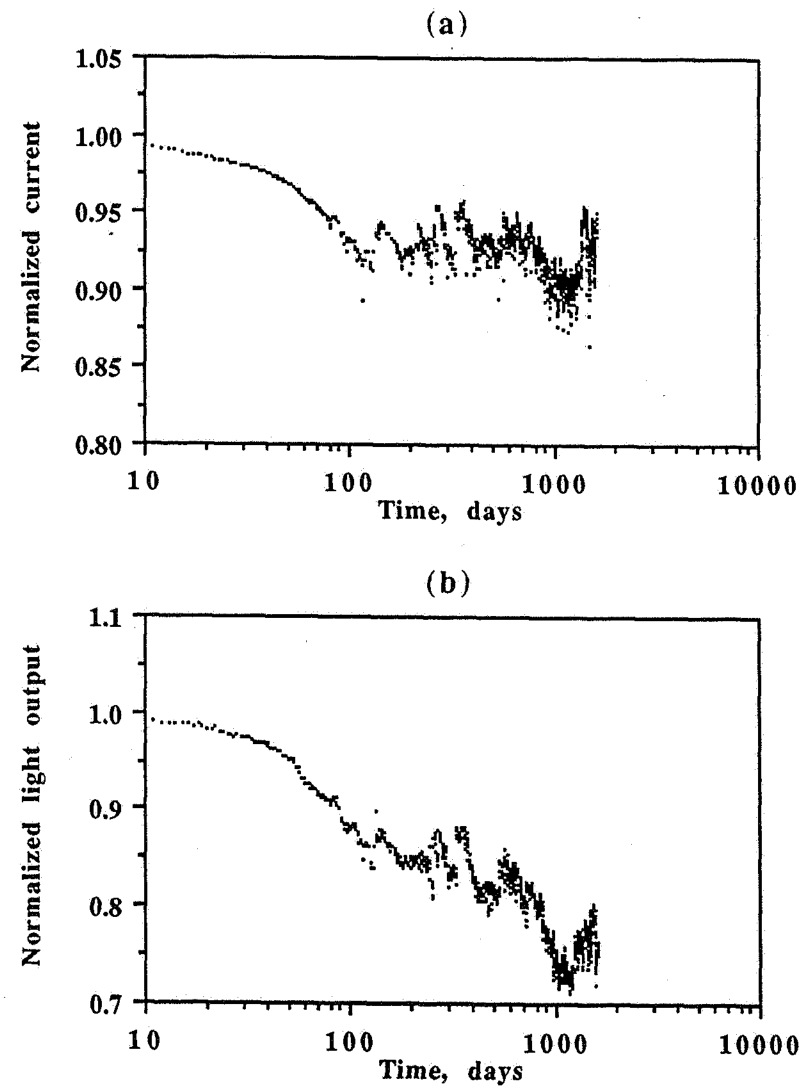


Figure A81. Lamp #40 of Experiment #4. This lamp burned-out after 1601 days of operation. No pre-life test characterization was performed on this lamp. (a) Lamp current vs. days of operation. (b) Lamp light output vs. days of operation.

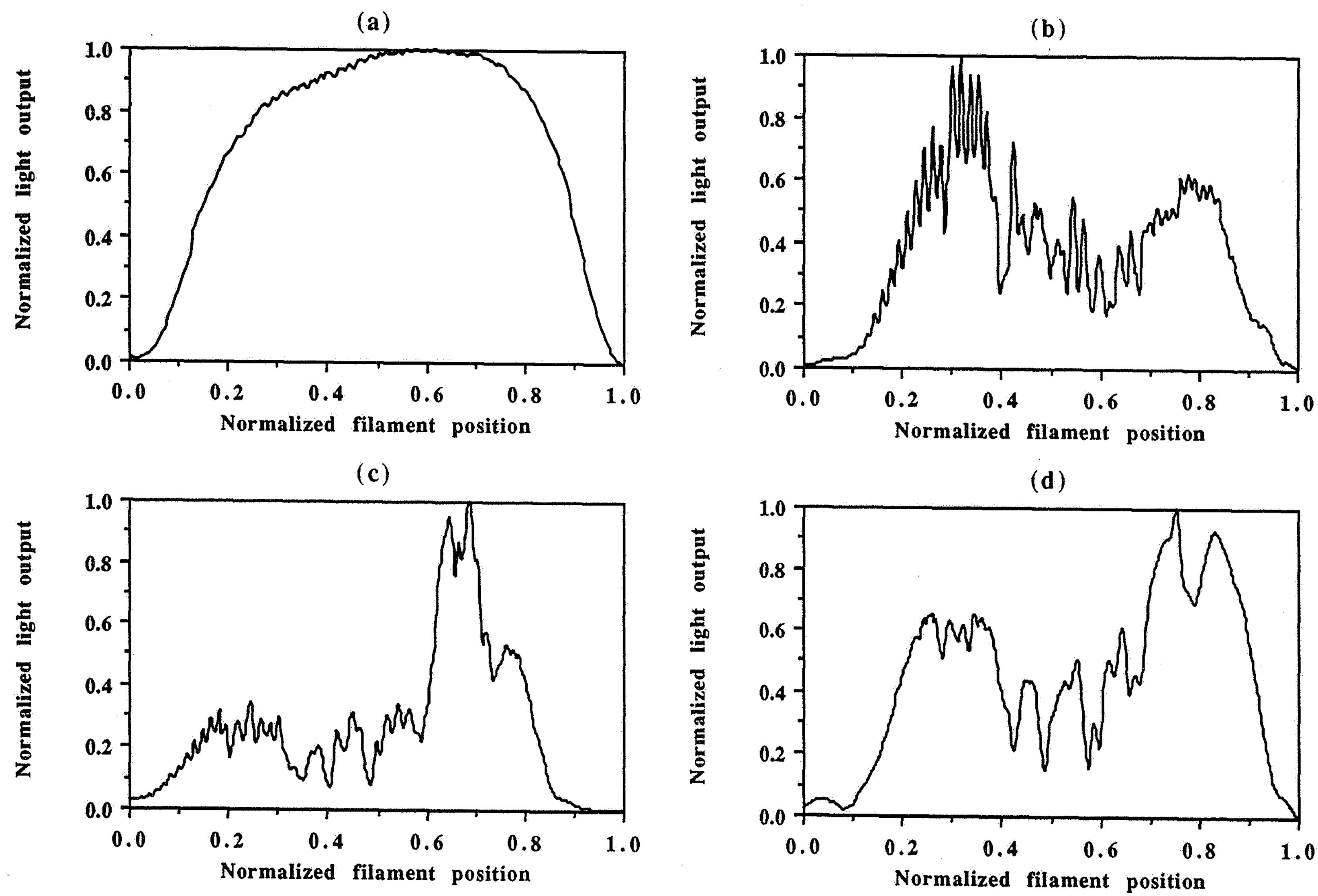


Figure A82. Lamp #40 of Experiment #4. These graphs show the light output from the lamp as a function of location along the filament. Severe distortion of the filament occurred during the life test. (a) 1 day of operation. (b) 463 days of operation. (c) 896 days of operation. (d) 1349 days of operation.

SBRC part number: none
Filament material: GE-218W
Filament diameter: 38.2 μm
Filament length: not measured
Number of turns: not measured
Post contact technique: welded
Operating voltage: 4.677 volts +0.003,-0.005
Burn-in time: none

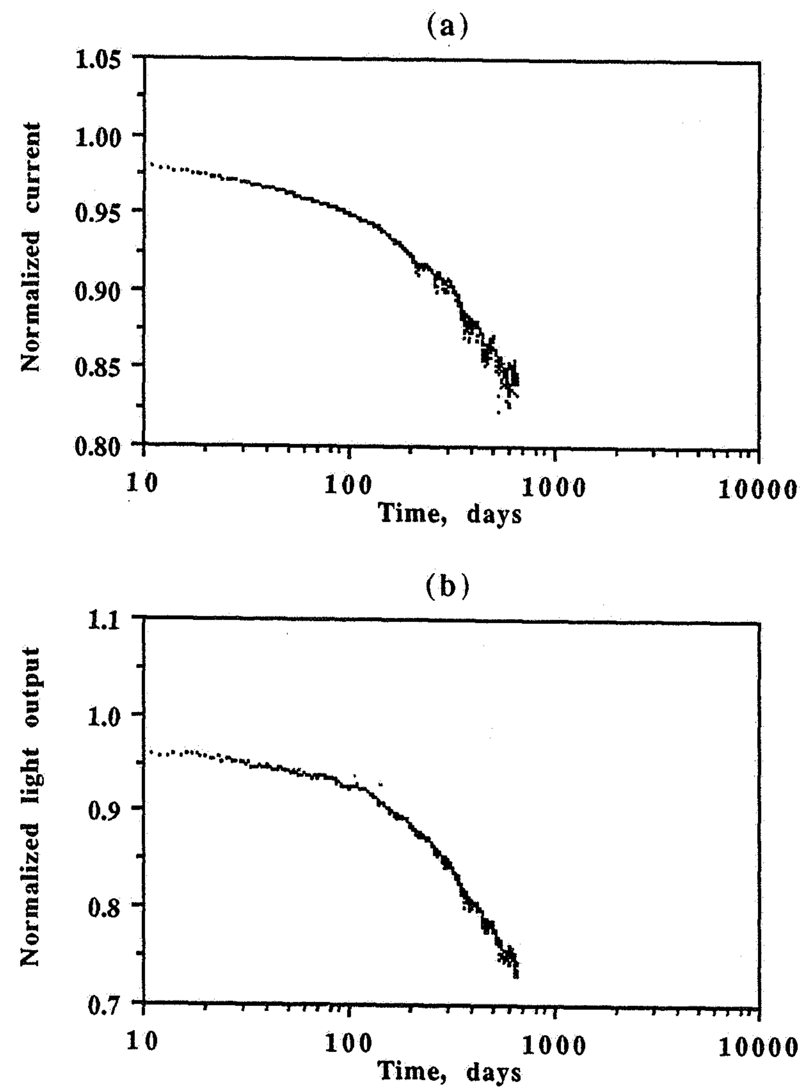


Figure A83. Lamp #41 of Experiment #4. This lamp burned-out after 659 days of operation. No pre-life test characterization was performed on this lamp. (a) Lamp current vs. days of operation. (b) Lamp light output vs. days of operation.

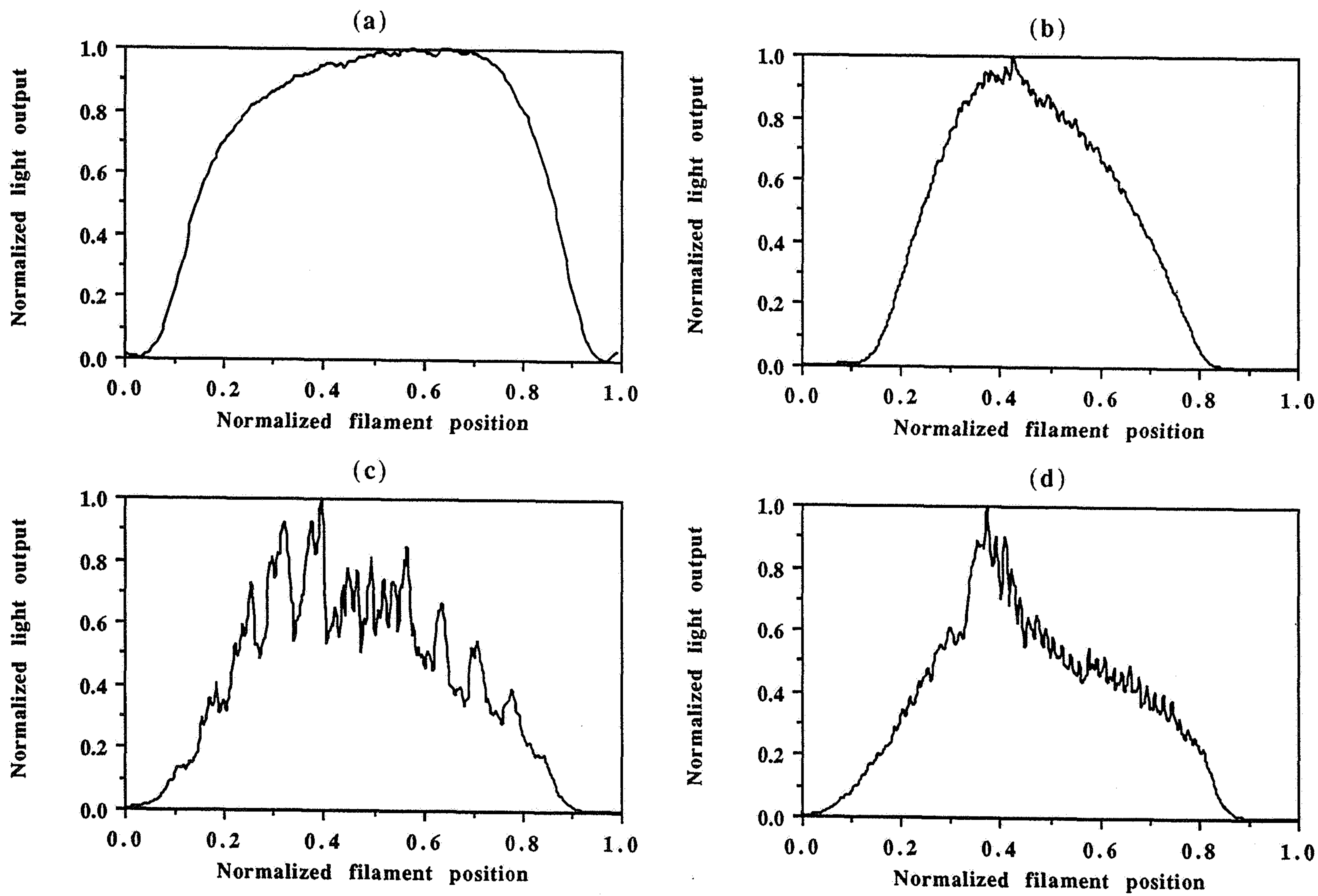


Figure A84. Lamp #41 of Experiment #4. These graphs show the light output from the lamp as a function of location along the filament. (a) 1 day of operation. (b) 192 days of operation. (c) 463 days of operation. (d) 637 days of operation.

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13. ABSTRACT *(Maximum 200 words)*

The aging characteristics and lifetimes of tungsten filament encoder lamps have been determined as a function of operating voltage and filament material. For pure tungsten and thoria-doped (1 percent) filament lamps, crystal grain growth over the center portion of the filament leads to the ultimate failure of the lamp. The development of notches associated with this grain growth is the cause of lamp burn out. Eventually, one of the notches will "etch" through the filament, causing it to fail open. For rhenium-doped (3 percent) filament lamps, distortion of the filament leads to the ultimate failure of a lamp. The lifetime of these lamps is about 1 year at an operating voltage of 5.0 volts. The pure tungsten filament lamps have the longest average lifetime, and the thoria-doped filament lamps have the shortest at 5.0 volts. The lifetime of these lamps is about 7 years at an operating voltage of 3.5 volts. Data suggest that the rhenium-doped lamps will have the longest average lifetime at 3.5 volts, and the thoria-doped will have the shortest. These lifetimes are comparable to the desired lifetime of 7 years.

14. SUBJECT TERMS
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